



Eco Logic International Gas-Phase Chemical Reduction Process— The Reactor System

Applications Analysis Report



SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

Eco Logic International Gas-Phase Chemical Reduction Process—The Reactor System

Applications Analysis Report

Risk Reduction Engineering Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268



Foreword

The SITE Program was authorized in the 1986 Superfund Amendments and Reauthorization Act (SARA). The program is administered by EPA's Office of Research and Development (ORD). The purpose of the program is to accelerate the development and use of innovative cleanup technologies applicable to Superfund and other hazardous waste sites. This is accomplished through technology demonstrations designed to provide performance and cost data on selected technologies.

The SITE Program funded a field demonstration to evaluate the ECO LOGIC Gas-Phase Chemical Reduction Process, developed by ELI Eco Logic International, Inc., Ontario, Canada. The ECO LOGIC Demonstration took place at the Middleground Landfill in Bay City, Michigan, using landfill waste; it assessed the technology's ability to treat hazardous wastes, based on performance and cost. Three reports contain the results of the demonstration: a Technology Evaluation Report (TER), which describes the field activities and laboratory results; this Applications Analysis Report (AAR), which interprets the data and discusses the applicability of the technology to liquid feedstocks; and a second, independent AAR, which interprets the data and discusses the applicability of the Thermal Desorption Unit (TDU) to soil feedstocks.

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E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

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Notice

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Abbreviations

AAQ	ambient air quality
AAR	Applications Analysis Report
AAS	atomic absorption spectroscopy
ALR	analytical linear range
ASTM	American Society for Testing and Materials
BOC	beginning of condition
BOR	beginning of run
Btu/lbm	British Thermal Unit per pound mass
ARARs	applicable or relevant and appropriate requirements
C	carbon
CAA	Clean Air Act
CB	chlorobenzene
CEM	continuous emission monitor
CEMS	continuous emissions monitoring system
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cfm	cubic feet per minute
CFR	Code of Federal Regulations
CIMS	Chemical Ionization Mass Spectrometer
Cl	chloride
Cl ₂	chlorine
CO	carbon monoxide
CO ₂	carbon dioxide
CP	chlorophenols
CVAAS	cold vapor atomic absorption spectroscopy
CWA	Clean Water Act
dP	pressure differential
DE	destruction efficiency
DOT	U.S. Department of Transportation
DRE	destruction and removal efficiency
dscm	dry standard cubic meter
dscf	dry standard cubic foot

Abstract

This report evaluates the capability of the ECO LOGIC Gas-Phase Chemical Reduction Process to detoxify organics in a liquid matrix. The report presents data from the recent EPA SITE Demonstration of the reactor system, provides case studies, and evaluates the costs of operating the system.

The ECO LOGIC Reactor System thermally separates organics, then chemically reduces them in a hydrogen atmosphere, converting them to a reformed gas that consists of light hydrocarbons and water. A scrubber treats the reformed gas to remove hydrogen chloride and particulates. Of this gas, a portion recycles back into the reactor; the remainder is either compressed for storage or feeds a propane-fired boiler prior to release to the atmosphere. The reactor system produced two principal residual streams: reformed gas and scrubber effluent.

The SITE Program evaluated the ECO LOGIC Process at the Middleground Landfill in Bay City, Michigan. The reactor system processed 2.9 tons of wastewater and 0.2 tons of waste oil, both contaminated with polychlorinated biphenyls (PCBs). The reactor system demonstration revealed that the process can successfully treat both Toxic Substance Control Act (TSCA) and Resource Conservation and Recovery Act (RCRA) hazardous compounds. Although the reactor is not classified as an incinerator, stack emissions met the TSCA destruction and removal efficiency for PCBs and the RCRA destruction and removal efficiency for tracer compounds, which are specified in the respective incinerator regulations. The system produced liquid effluent streams that may require further treatment prior to publicly owned treatment works (POTW) processing.

The ECO LOGIC Process is best suited to sites that contain oily liquid wastes. Costs fell in the range of \$7.68/gal (60% utilization) to \$6.41/gal (80% utilization) for liquid feed. The ECO LOGIC Thermal Desorption Unit (TDU)/Reactor System Demonstration, a proof-of-concept test that processed contaminated soil, is the topic of a second, independent AAR.

Abbreviations (Continued)

OSHA	Occupational Safety and Health Act
OSWER	Office of Solid Waste and Emergency Response
PAHs	polycyclic aromatic hydrocarbons
PCBs	polychlorinated biphenyls
PCDD	polychlorinated dibenzo(p)dioxin
PCDF	polychlorinated dibenzofuran
PCE	perchloroethylene (tetrachloroethene)
pH	a measure of acidity/alkalinity
PICs	products of incomplete combustion
PIR	product of incomplete reduction
POHC	principal organic hazardous constituent
POTW	publicly owned treatment works
PPE	personal protective equipment
ppb	parts per billion
ppm	parts per million
ppmv	parts per million by volume
psi	pounds per square inch
psig	pounds per square inch gauge
QA	quality assurance
QI	quality indicator
RCRA	Resource Conservation and Recovery Act
RREL	Risk Reduction Engineering Laboratory
SARA	Superfund Amendments and Reauthorization Act
S	sulfur
sec	second
scf	standard cubic feet
scfm	standard cubic feet per minute
SITE	Superfund Innovative Technology Evaluation Program
SO ₂	sulfur dioxide
SVOC	semivolatile organic compounds
TCLP	Toxicity Characteristic Leaching Procedure
TDU	thermal desorption unit
TER	Technology Evaluation Report
THC	total hydrocarbons
TSCA	Toxic Substances Control Act
TSD	treatment, storage, and disposal
µg	microgram
VOC	volatile organic compounds
VOST	volatile organic sampling train
WTC	Wastewater Technology Center

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Section 1

Executive Summary

Introduction

This report summarizes the findings of the SITE Demonstration of the Gas-Phase Chemical Reduction Process developed by ELI Eco Logic International, Inc. (ECO LOGIC) of Ontario, Canada.

Under the auspices of the SITE Program, and in cooperation with the City of Bay City, Michigan; Environment Canada; and the Ontario Ministry of the Environment and Energy; EPA conducted the demonstration of the ECO LOGIC Process at Bay City's Middleground Landfill. The landfill accepted municipal and industrial wastes for approximately 40 years. A 1991 remedial investigation indicated elevated levels in groundwater of trichloroethene, PCBs, 1,2-dichloroethene, methylene chloride, toluene, and ethylbenzene. The groundwater contained lesser concentrations of benzidine, benzene, vinyl chloride, chlorobenzenes, polycyclic aromatic hydrocarbons (PAHs), lindane, dieldrin, chlordane, and DDT metabolites.

The patented ECO LOGIC Gas-Phase Chemical Reduction Process treats organic hazardous waste in a hydrogen-rich atmosphere at approximately 900°C (1,650°F) and ambient pressure to produce a reformed gas. The reaction products include hydrogen chloride from the reduction of chlorinated organics, such as PCBs, and lighter hydrocarbons, such as methane and ethylene, from the reduction of straight-chain and aromatic hydrocarbons. The absence of free oxygen in the reactor inhibits dioxin formation. Water acts as a hydrogen donor to enhance the reaction.

A scrubber treats the reformed gas to remove hydrogen chloride and particulates. Of this gas, 95% recycles back into the reactor; 5% feeds a propane-fired boiler prior to release to the atmosphere. The recycle stream may be used as a fuel in other system support equipment, such as the boiler that generates steam. The final combustion step in the boiler met the RCRA requirements, making the reformed gas environmentally acceptable for combustion.

The SITE Demonstration

The two-part demonstration took place in October and December 1992, using PCB-contaminated oil, water, and soil extracted directly from the landfill. ECO LOGIC first performed a series of shakedown tests to establish optimum

system performance. Two liquid tests investigated reactor performance (Conditions 1 and 3); a soil test (Condition 2) studied a complementary TDU, the topic of a second, independent AAR. Each reactor test condition consisted of three runs. The reactor program treated approximately 2.9 tons of wastewater and 0.2 tons of waste oil. This report presents only the results of the reactor tests. The program also conducted a 72-hour test to evaluate the reactor system reliability.

EPA collected extensive samples at points around the major system components and stored or logged important data on system operation and utility usage. Laboratory analyses provided information on the principal process streams: reactor grit, scrubber residuals, reformed gas, and boiler stack emissions. EPA evaluated these data against established program objectives to determine the capability of the process to treat the designated waste.

Conclusions

Based on the program objectives, the demonstration confirmed the feasibility of the gas-phase chemical reduction process for treating PCBs and other chlorinated organic compounds, producing a fuel gas from contaminated liquids and providing environmentally acceptable air emissions.

In general, ECO LOGIC's Reactor System effectively destroyed PCBs, reducing them to lighter hydrocarbons. Theoretically, the destruction process could depend on both the reactor system's gas phase reduction reactions, which produced the reformed gas, and on the propane/reformed gas-fired boiler, a combustion device.

Although the result was not listed as a primary or secondary objective for the demonstration, destruction and removal efficiencies (DREs) for PCBs in the scrubbed reformed gas were essentially equal to the DREs achieved at the boiler stack. This shows that combustion of the reformed gas in the boiler is not required to complete PCB destruction.

Stack emissions generally met stringent regulatory levels. However, average benzene concentrations in the stack gas—corrected to 7% oxygen—(Condition 1 - 73 µg/dscm; Condition 3 - 113 µg/dscm) and scrubber liquor (Condition 1 - 18.5 µg/L; Condition 3 - 347 µg/L) required close monitoring. The reformed gas composition resembled coal-gas fuel. The scrubber liquor required either disposal as a RCRA waste or

Abbreviations (Continued)

ECO LOGIC	ELI Eco Logic International, Inc.
EPA	U.S. Environmental Protection Agency
EER	Energy and Environmental Research Corporation
FID	flame ionization detection
FPD	flame photometric detector
ft	feet
FWEI	Foster Wheeler Enviresponse, Inc.
g	gram
gal	gallon
GC	gas chromatography
GF	graphite furnace
gr	grains
gpm	gallons per minute
HR	high resolution
hr	hour
H ₂	hydrogen
HCB	hexachlorobenzene
HCl	hydrogen chloride
ICAP	inductively coupled argon plasma spectroscopy
in.	inches
kg	kilogram
Kw	kilowatt
L	liter
lb	pound
m	meter
MASA	Method of Air Sampling and Analysis
MDNR	Michigan Department of Natural Resources
mg	milligram
min	minute
mo	month
MS	mass spectroscopy
NAAQS	National Ambient Air Quality Standards
NDIR	non-dispersive infrared
NDUV	non-dispersive ultraviolet
ng	nanogram
NO _x	nitrogen oxides
NPDES	National Pollutant Discharge Elimination System
O ₂	oxygen
ORD	Office of Research and Development

Table 1. Summary Results of Reactor System Tests

Objective	Results		Conclusions
	Met	Not Met	
Demonstrate DRE for PCBs: 99.9999%	X		Good destruction.
Demonstrate DE for PCE: 99.99%	X		Good destruction.
Ensure no formation PCDD/PCDF	X		No net PCDD/PCDF formation.
Characterize PIC emissions	X		PICs characterized; benzene emissions exceeded regulatory limit.
Characterize HCl emissions	X		Acceptable emissions.
Document MDNR air permit compliance	X		Air permit compliance documented; benzene emissions exceeded MDNR conditions.
Characterize criteria air pollutants	X		Easily met permit conditions.
Document TSCA permit compliance	X		Met permit conditions.
Validate key cost assumptions	X		Cost elements identified.
Characterize effluents and residuals	X		Organics destroyed; metals partitioned to scrubber effluents; after further treatment, scrubber liquor may be suitable for POTW.
Determine suitability of reformed gases for reuse/resale	X		Closely matched composition of other commercial fuel gases.
Demonstrate system reliability	X		Process reliability requires improvement.
Develop mass balances	X		Generally good closures, except for certain metals.
Characterize scale-up parameters	X		Characterized.
Validate CIMS		X	May reflect data trends useful for process control.
Document system operation	X		Data available for commercial scale-up.

SI Conversion Factors

	Multiply	English (US) Units	by	Factor	to get	Metric (SI) Units
Area:		1 ft ²		0.0929		m ²
		1 in. ²		6.452		cm ²
Flow rate:		1 gal/min		6.31 x 10 ⁻⁵		m ³ /s
		1 gal/min		0.0631		L/s
		1 MGD		43.81		L/s
Length:		1 ft		0.3048		m
		1 in.		2.54		cm
Mass:		1 lb		453.59		g
		1 lb		0.45359		kg
Volume:		1 ft ³		28.316		L
		1 ft ³		0.028317		m ³
		1 gal		3.785		L
		1 gal		0.003785		m ³
Temperature:		°F - 32		0.55556		°C
Concentration:		1 gr/ft ³		2.2884		g/m ³
		1 gr/gal		0.0171		g/L
		1 lb/ft ³		16.03		g/L
Pressure:		1 lb/in. ²		0.07031		kg/cm ²
		1 lb/in. ²		6894.8		Newton/m ²
Heating value:		Btu/lb		2326		Joules/kg
		Btu/scf		37260		Joules/scm

important tool in the development and commercialization of the technology.

Key Contacts

The sources listed below can provide additional information concerning the SITE Demonstration, the site, or the ECO LOGIC Gas-Phase Chemical Reduction Process.

Gordon M. Evans
SITE Project Manager
U.S. Environmental Protection Agency
26 W Martin Luther King Drive (MS-215)
Cincinnati, OH 45268
Phone: 513-569-7684
Fax: 513-569-7620

James Nash
ELI Eco Logic International, Inc.
143 Dennis St.
Rockwood, Ontario N0B 2K0
Canada
Phone: 519-856-9591
Fax: 519-856-9235

recycling through the system for additional treatment. Table 1 correlates the program conclusions with program objectives.

Waste Applicability

The SITE Program concluded that the ECO LOGIC Process efficiently treated liquid wastes containing oily PCBs, other organics, and water containing PCBs, other organics, and metals. Stack emissions met stringent regulatory levels. The principal residual stream—the scrubber effluent—concentrated metals and some organics (benzene, PCBs, and PAHs), indicating that additional treatment might be required prior to disposal.

The reactor did not directly process soil. Instead, ECO LOGIC provided a complementary front-end TDU to treat soils. An

independent AAR presents the results of the TDU (Condition 2) tests.

Costs

The 12 categories established for the SITE Program formed the basis for the cost analysis. Costs relate to the reactor system, processing an average of 2.2 kg/min, as operated at the Middleground Landfill. Based on the economic analysis, the estimated cost (1994 U.S. dollars) for treating liquid wastes similar to those at the Bay City site range from \$2,000/ton (60% utilization factor) to \$1,670/ton (80% utilization factor). The most important element affecting cost is labor (52% of cost), followed by site preparation (15%), supplies (12%), and start-up/mobilization (12%).

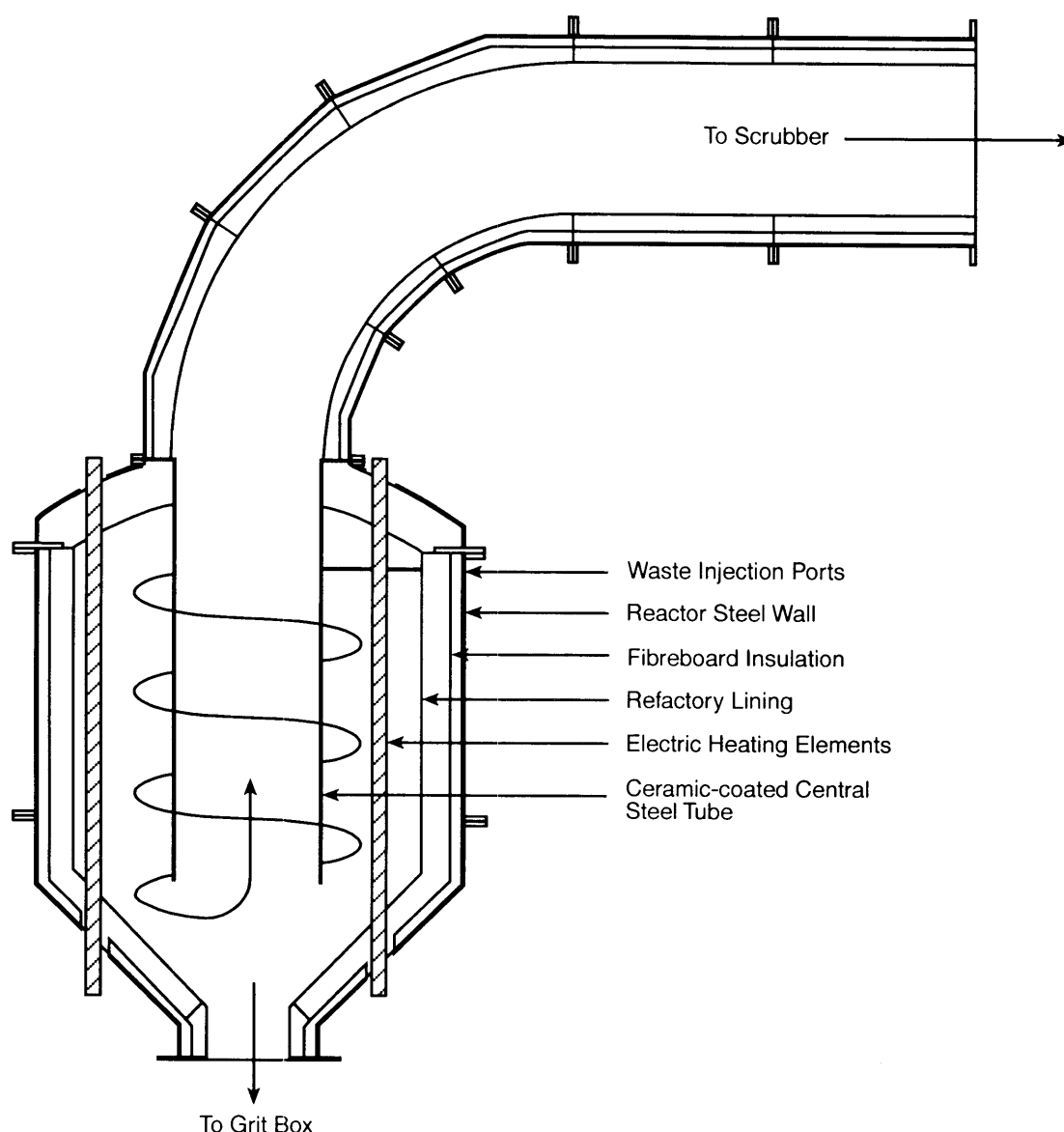


Figure 3. The ECO LOGIC reactor.

Technology Evaluation

The demonstrated ECO LOGIC Gas-Phase Chemical Reduction Process is a pilot or small commercial-scale, trailer-mounted system, capable of treating wastewater and waste oil. The SITE Demonstration of the reactor system consisted of initial shakedown runs, a blank run to determine train capacities, and six liquid runs (Conditions 1 and 3). An independent AAR discusses the TDU (Condition 2) demonstration results.

A liquid pool of waste within the Middleground Landfill provided feedstock for the tests. Test Condition 1 treated 1.73 kg/min (totalling 2.9 tons) of wastewater containing 3,757 ppm PCBs. Condition 3 treated 0.385 kg/min (totalling 0.2 tons) of waste oil containing 25.4% (254,000 ppm) PCBs.

PCB concentrations were sufficient to calculate the DREs. PCE added to the feedstock at levels of 3,209 and 6,203 ppm respectively, served as a tracer to determine DEs. Additional feedstock contaminants included fluoranthene, naphthalene, phenanthrene, other PAHs, chlorobenzene, chlorophenol, methyl chloride, tetrachlorethene, toluene, and various metals.

Based on the SITE test data—covered in detail in the TER—analysts assessed the applicability of the ECO LOGIC Process to the test wastes, as summarized in Table 1 and as discussed in the following paragraphs.

Section 2

Introduction

The SITE Program

In 1986 EPA's Office of Solid Waste and Emergency Response (OSWER) and ORD established the SITE Program to promote the development and use of innovative technologies to clean up Superfund sites across the country. Now in its eighth year, SITE is helping to commercialize the treatment technologies necessary to meet new federal and state cleanup standards aimed at permanent remedies, rather than short-term corrections. The SITE Program includes four major elements: the Demonstration Program, the Emerging Technologies Program, the Measurement and Monitoring Technologies Program, and the Technology Transfer Program.

The major focus has been on the Demonstration Program, designed to provide engineering and cost data on selected technologies. EPA and the technology developers that participate in the program share the cost of the demonstration. Developers are responsible for demonstrating their innovative systems, usually at Superfund sites selected by EPA. EPA is responsible for sampling, analyzing, and evaluating test results. The outcome is an assessment of the technology's performance, reliability, and cost. This information, used in conjunction with other data, enables EPA and state decision makers to select the most appropriate technologies for Superfund cleanups.

Innovative technology developers apply to participate in the Demonstration Program by responding to EPA's annual solicitation. EPA will consider a proposal at any time from a developer who has scheduled a treatment project on Superfund waste. To qualify for the program, a new technology must have a pilot- or full-scale unit and offer some advantage over existing technologies. Mobile technologies are particularly interesting.

Once a proposal has been accepted, EPA and the developer work with the EPA regional offices and state agencies to identify a site containing wastes suitable for testing the technology. EPA prepares a detailed sampling and analysis plan designed to thoroughly evaluate the technology by providing analysts with reliable data. A demonstration may last anywhere from a few days to several months, depending on the process and the quantity of waste needed to assess the technology. Ultimately, the Demonstration Program rates the technology's overall applicability to Superfund problems.

The second major element of the SITE Program is the Emerging Technologies Program, which fosters the further investigation and development of treatment technologies that are still at laboratory scale. Successful validation of these technologies could lead to the development of systems viable for field demonstration. A third component of the SITE Program, the Measurement and Monitoring Technologies Program, provides assistance in the development and demonstration of innovative technologies that will better characterize Superfund sites. The Technology Transfer component ensures effective dissemination of the results of the demonstration projects.

SITE Program Reports

Two documents incorporate the results of each SITE Demonstration: the TER and the AAR. The TER contains a comprehensive description of the demonstration and its results. This report assists engineers who are performing a detailed evaluation of the technology for a specific site and waste. The technical evaluations provide a detailed understanding of the technology performance during the demonstration and assess the advantages, risks, and costs for a given application.

The AAR estimates Superfund applications and technology costs, based on available data. It compiles design and test data, summarizes them, explores other laboratory and field applications, and discusses the advantages, disadvantages, and limitations of the technology. The AAR attempts to synthesize available information and draw reasonable conclusions for the technology's use. The report discusses factors such as site and waste characteristics that have a major effect on costs and performance. Pilot- and full-scale operations data provide the bases for estimating technology costs for different applications.

The amount of available data needed to evaluate an innovative technology varies widely. Data may be limited to laboratory tests on synthetic waste or may extend to performance data on actual wastes treated in the field at the pilot or full scale. In addition, conclusions regarding Superfund applications drawn from a single field demonstration have limitations. A successful field demonstration does not necessarily ensure that a technology will become widely applicable or attain full development at the commercial scale. The AAR can assist remedial managers in planning Superfund cleanups; it represents an

Criteria Air Pollutants

During the tests, continuous emission monitors (CEMs) measured the concentrations of the criteria air pollutants at the stack: nitrogen oxides (NO_x), sulfur dioxide (SO₂), particulates, THC, and CO. Each of these pollutant emission concentrations was low, well under the level established in the MDNR air permit. NO_x averages ranged from 60.8 to 63.5 ppmv; SO₂, from 1.4 to 2.2 ppmv; particulates, from 0.17 to 0.99 mg/dscm; THC, from 1.53 to 15.5 ppmv; and CO, from 2.3 to 23.3 ppmv (all corrected to 7% O₂, dry basis). The system can be expected to achieve similar results at other sites.

The demonstration-scale boiler operated between high and low fire, depending on the system's steam requirements. The test analyses showed out-of-range spike concentrations of THC and CO (indicators of combustion efficiency) during low-fire operation, most notably in Condition 1, Run 1 when the boiler was cycling between high and low fire. Future users must be alert to the potential for decreased combustion efficiency and increased emissions of criteria air pollutants during low-fire operation. The boiler should be operated at firing rates and air/fuel ratios that prevent these spikes. Since the

DREs were adequate in the scrubbed reformed gas, reduced combustion efficiency in the boiler will not affect the ability of the reactor process to destroy hazardous organics.

HCl

The ECO LOGIC Reactor System reduced stack HCl emissions to below the MDNR-permitted levels. RCRA emission limits set incinerator HCl emissions at 4 lb/hr (or less), or 99% removal. The reactor system easily achieved this—average stack concentrations ranged from 0.66 mg/dscm at 109 mg/hr to 0.81 mg/dscm at 198 mg/hr. Removal efficiencies reached 99.98%. Most of the chlorine in the feedstock accumulated in the scrubber effluent.

MDNR Permit Compliance

Table 2 compares the test results to the conditions imposed by the MDNR air permit. Of the 15 permit criteria, only benzene stack concentrations exceeded the permit criteria. However, the total quantity of emitted materials is low, probably lower than levels that normally present health risks to exposed populations. For future commercial units, a taller stack might resolve this problem; greater dispersion could allow less

Table 2. MDNR Air Permit Conditions

Parameter	Unit	Permit limit	Program average
HCl (7% O ₂ , dry basis)	mg/dscm lb/hr	5.2 0.027	<0.67 <0.00034
THC as methane (7% O ₂ , dry basis)	ppmv lb/hr	200 0.19	5.5 0.0016
CO (7% O ₂ , dry basis)	ppmv lb/hr	100 0.15	11.0 0.0059
PCBs (dry basis)	mg/dscm lb/hr	0.09 0.00048	0.00060 3.3E-07
Benzene (dry basis)	µg/dscm lb/hr	20 0.00009	65 >0.000034
Chlorobenzenes as 1,2,4-trichlorobenzene (dry basis)	µg/dscm lb/hr	1 0.000002	(ND) <0.88 4.3E-07
Opacity	%	0	0
Scrubber inlet temperature	°C	>35	520
Scrubber solution	pH	>8	8.9
On-line mass spectrometer	Yes/No	Yes	Yes
Reactor temperature	°C	>850	907
Reactor pressure	in. H ₂ O	<10	1.97
System oxygen	%	<0.04	0.045
Gas booster dP	in. H ₂ O	<16	9.57
Recirculation flow rate	cfm	100	110

ND Not detected.

BQL Detected below the quantitation limit.

< Emission rate is less than the mass indicated. The mass indicated assumes that the substance is present at the detection limit.

Section 3

Technology Applications Analysis

This AAR assesses the capability of the ECO LOGIC Process to treat liquids contaminated with PCBs and other hazardous substances. EPA has based the assessment on the results of the SITE Demonstration and on data supplied by the technology developer. The report contains a summary of relevant material from the more detailed TER. Since the results of the demonstration that are provided in the TER are of known quality, the report bases its conclusions on them.

Appendix A describes the demonstration sampling and analytical locations/methods; Appendix B, ECO LOGIC's claims for the technology; and Appendix C, case studies of the technology's application.

Process Description

The patented ECO LOGIC Gas-Phase Chemical Reduction Process treats organic hazardous waste in a hydrogen-rich atmosphere at approximately 900°C (1,650°F) and ambient pressure, producing a reformed gas. Water acts as a hydrogen donor to enhance the reaction. The reaction products include HCl, from the reduction of chlorinated organics, such as PCBs, and lighter hydrocarbons, such as methane and ethylene from the reduction of straight-chain and aromatic hydrocarbons. A scrubber treats the reformed gas to remove hydrogen chloride and particulates. Of this gas, a portion recycles back into the reactor; the remainder is either compressed for storage or feeds a propane-fired boiler prior to release to the atmosphere. The absence of free oxygen in the reactor inhibits dioxin formation.

Figure 1 shows some of the reactions that lead to the major intermediate and final products. Through hydrogenation, the first five reactions remove chlorine from PCBs and reduce the higher molecular weight hydrocarbons to simpler, more saturated compounds. The final reaction regenerates hydrogen.

Figure 2 illustrates the process in a schematic diagram of the field demonstration unit. The demonstration-scale reactor (Figure 3) was 2 m (6 ft) in diameter and 3 m (9 ft) tall, mounted on a 15 m (45 ft) drop-deck trailer. The trailer carried a scrubber system, a recirculation gas system, and an electrical control center. A second trailer held a propane boiler, a waste preheating vessel, and a waste storage tank.

ECO LOGIC designed the process to treat 4 tons/day of waste oil, 10 tons/day of wastewater, and 25 tons/day of soil, de-

pending on the nature of the contaminants, their degree of chlorination, and their water content. The ECO LOGIC TDU—designed to remove most volatile, most semivolatile, and some metallic contaminants—treats the soil. The TDU is the subject of an independent AAR.

For the demonstration, a heat exchanger evaporated contaminated aqueous feedstock to form steam and a concentrated heated liquor. Atomizing nozzles sprayed the heated liquor, with associated particulates, into the reactor. A separate pump sent PCB-rich oils directly to the reactor through other atomizing nozzles. Compressed hydrogen-rich recirculation gas passed through a gas-fired heat exchanger and entered the top of the reactor tangentially. The tangential entry swirled the fluids to provide effective mixing. As indicated in Figure 3, the swirling mixture traveled downward in the annulus formed by the reactor wall and the central ceramic-coated steel tube, past electrically heated bars. These bars heated the mixture to 900°C (1,650°F). At the bottom of the reactor the mixture entered the tube, reversed direction, and flowed upward to the outlet of the reactor. The reduction reactions occurred as the gases traveled from the reactor inlets to the scrubber inlet.

After quenching, the gases flowed through a scrubber where contact with water removed hydrogen chloride and fine particulates. A large water-sealed vent, acting as an emergency pressure relief duct, passed scrubber water to a tank below. A pump recirculated the scrubber water in a loop through an evaporative cooler to reduce its temperature to 35°C (95°F). Caustic and make-up water, added to the scrubber liquor, maintained HCl removal efficiency. The scrubber produced two effluent streams: sludge and decant water.

The reformed gas exiting the scrubber contained excess hydrogen, lighter hydrocarbon reduction products such as methane and ethylene, and a small amount of water vapor. A portion of this hydrogen-rich gas was reheated to 500°C (930°F) and recirculated back into the reactor; the remainder of the gas served as supplementary fuel for a propane-fired boiler. The boiler produced steam used in the heat exchanger and burned the reformed gas, which was the only air emission from the process.

When treating wastes containing highly concentrated organics, the process generates excess reformed gas. The system can compress the reformed gas and store it for later use as fuel in other parts of the process.

Table 4. Component Partitioning

Component	Condition	Stream (ppb)*				
		SS1 Waste- water	SS2 Waste Oil	SS11 Reactor Grit	SS12 Scrubber Sludge	SS13 Scrubber Decant
Total PCBs (mono-deca)	1	22.8	2.38E+08	2,160,000	15,490	203
	3	25.2	2.54E+08	3,310	17,665	40.6
Total PAHs	1	ND	320,400	655,000	12,800,000	6,640
	3	24.8	366,000	846,000	40,700,000	15,200
Total PCDD/PCDF	1	0.00054	327	0.179	4.03	0.00063
	3	1.57	393	162	1.92	0.00013
Total chlorobenzenes	1	ND	253,500	ND	ND	ND
	3	ND	235,000	ND	ND	ND
Total chlorophenols	1	ND	ND	ND	ND	ND
	3	ND	ND	ND	ND	ND
Benzene	1	3.7 ¹	3 ¹	430	ND	7,160
	3	8.7	ND	17,000 ²	ND	7,700 ²
PCE	1	2 ¹	ND	ND	ND	ND
	3	4.3	ND	ND	ND	4 ¹

Component	Condition	SS22 Scrubber Liquor	SS14 Reformed Gas ³	SS15 Tank Condensate	SS18 Heat Exchanger	SS16 Stack ³
Total PCBs (mono-deca)	1	31.5	2.84	N/A	8.67	0.21
	3	48.9	32.6	16,800	10.79	1.23
Total PAHs	1	2,697	N/A	N/A	5.25	28.7 ⁴
	3	20,300	N/A	6,420,000	43.8 ⁴	24.04 ⁴
Total PCDD/PCDF	1	0.0004	0.00021	N/A	0.00021	0.0004
	3	0.001	0.000162	ND	0.00053	0.0002
Total chlorobenzenes	1	ND	ND	N/A	ND	ND
	3	ND	ND	ND	ND	ND
Total chlorophenols	1	ND	ND	N/A	ND	ND
	3	ND	ND	ND	ND	ND
Benzene	1	18.5	521,600 ²	N/A	9.3	73.1
	3	347	1,781,000	819 ²	120	113
PCE	1	ND	8.89	N/A	ND	3.85
	3	7	2.481	7.75 ¹	ND	4.51

¹ Compound(s) detected at concentrations below the quantitative limit.

² Compound detected at concentrations above the linear range for analysis.

³ Concentration given as µg/dscm.

⁴ Essentially naphthalene.

ND Not detected.

* Averages of three runs, including NDs.

Major Residual Streams

Reactor Grit—The first test run revealed that the reactor grit volume was small enough for exclusion as an effluent stream. Any accumulation can be either recycled or stored for permitted disposal after the treatment program.

Considering only PCB congeners that have three or more chlorine atoms (as defined by TSCA), PCB concentrations detected in the grit ranged from 1.67 to 2,100 ppm. A congener consists of all PCB compounds having the same number of chlorine atoms but arranged in different positions for any

individual congener compound. The grit from Condition 1 exceeded the 2 ppm (per congener) TSCA criterion. If monochlorobiphenyls, dichlorobiphenyls, and nondetected congeners (assumed to be present at the detection level) are included, the grit could contain maximum PCB concentrations between 3.3 and 2,160 ppm. These concentrations could affect the DE if the grit is considered a process output rather than a recycled stream. However, at the commercial-scale, ECO LOGIC plans to recirculate this stream through the reactor.

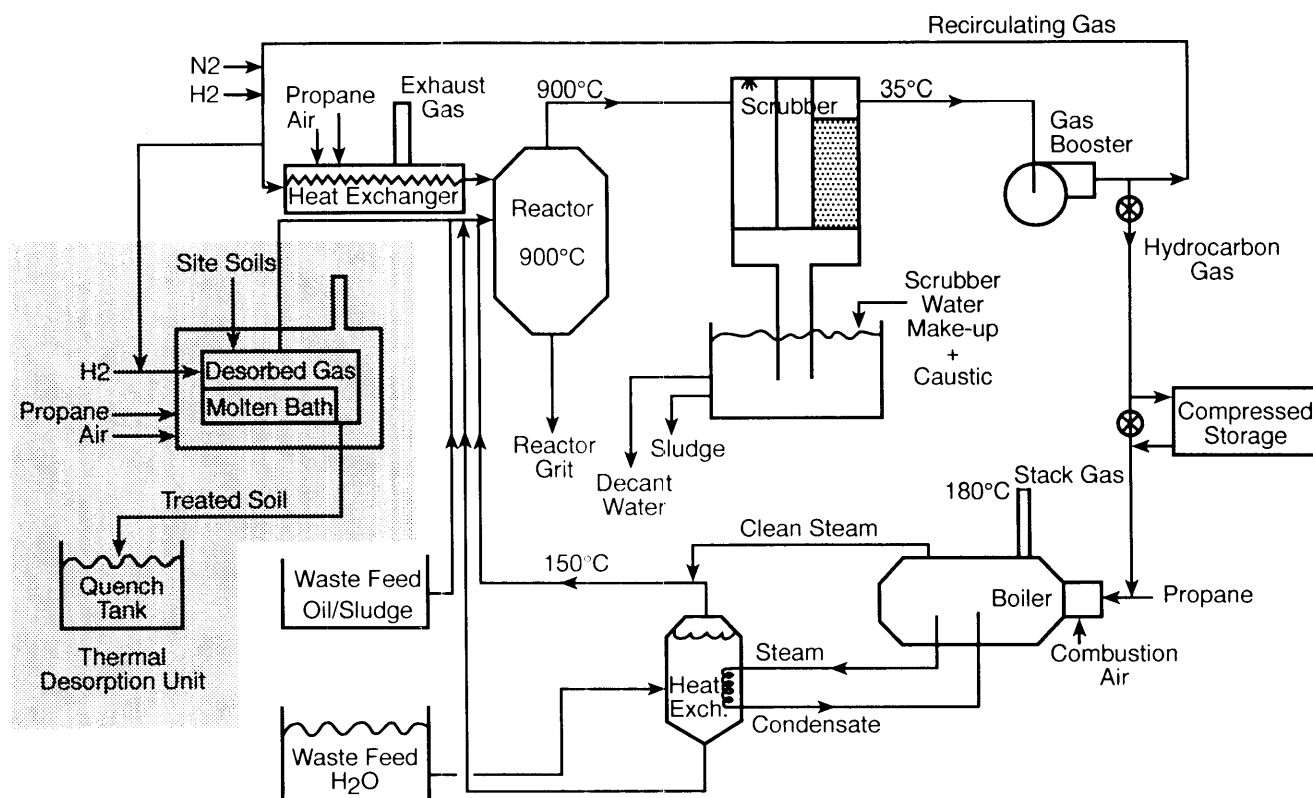


Figure 2. Reactor system and TDU schematic diagram.

- Document compliance with Michigan Department of Natural Resources (MDNR) air permit conditions.
- Characterize criteria air pollutant emissions.
- Document compliance with TSCA permit requirements.
- Validate key cost assumptions used in process economic analyses.
- Characterize effluents and residual streams relative to disposal requirements.
- Determine the suitability of the reformed gases for reuse/resale.
- Demonstrate system reliability.
- Develop a system mass balance, including metals.
- Characterize critical process scale-up parameters.
- Validate the ECO LOGIC Chemical Ionization Mass Spectrometer (CIMS).
- Document system operation during test runs.

Conclusions

Based on the program objectives, EPA found that the demonstration confirmed the feasibility of the gas-phase chemical reduction process for treating PCBs and other chlorinated organic compounds, producing a low Btu fuel gas from contaminated liquids and providing environmentally acceptable air emissions.

In general, ECO LOGIC's Reactor System effectively destroyed PCBs, reducing them to lighter hydrocarbons. Theoretically, the destruction process could depend on both the reactor system's gas phase reactions, which produced the reformed gas, and on the propane/reformed gas-fired boiler, a combustion device.

Although the result was not listed as a primary or secondary objective for the demonstration, DREs for PCBs in the scrubbed reformed gas were essentially equal to the DREs achieved at the boiler stack. This shows that combustion of the reformed gas in the boiler is not required to complete PCB destruction.

Stack emissions generally met stringent regulatory levels. However, average benzene concentrations in the stack gas—corrected to 7% oxygen—(Condition 1 - 73 µg/dscm; Condition 3 - 113 µg/dscm) and scrubber liquor (Condition 1 - 18.5 µg/L; Condition 3 - 347 µg/L) required close monitoring. The reformed gas composition resembled coal-gas fuel. The scrubber liquor required either disposal as a RCRA waste, or recycling through the system for additional treatment. Table 1 (Executive Summary) correlates the program conclusions with program objectives.

TSCA Permit Conditions

The program required that ECO LOGIC obtain a TSCA research and development permit. The permit conditions addressed PCB throughput and PCB concentrations in the effluent streams. TSCA established maximum PCB levels of 2 ppm per congener in soil and 3 ppb per congener in water streams. TSCA evaluated the combined scrubber liquid residual streams based on samples from the storage tanks. These samples met the criterion that allowed disposal in a commercial treatment system. However, the local POTW imposed stricter PCB effluent concentrations than those permitted by TSCA, requiring disposal of the liquid residuals through a RCRA-permitted facility. Since POTWs set their acceptance requirements based on their effluent requirements, acceptance/rejection of the scrubber liquid streams will be site-specific. In order for the ECO LOGIC system to process PCB materials, a TSCA permit will be required. The remedial manager should formulate a schedule that includes obtaining a TSCA permit and addressing any process and operating constraints that the permit may impose.

Equipment and Operating Considerations

The remedial manager considering the use of the ECO LOGIC Reactor Process should understand the function of major process equipment components and potential operating problems associated with them.

System Components

The principal components of the ECO LOGIC Reactor System are the reactor, the scrubber system, the recirculating fan, the propane-fired boiler, the liquid feed systems, and the process instrumentation. Each of these components presented operating problems that future users should consider.

Reactor—The reactor is the principal component of the system. Here the combination of temperature, residence time, feed rate, and hydrogen concentration determines the DE. The reliability and performance of the subsystems controlling these critical parameters affect the reformed gas quality and the appropriate disposition of process residues and emissions.

During the demonstration, the steam flow control valve, used to control reactor pressure, did not operate stably. Control improved as the operators gained experience, made system modifications, and formulated program logic adjustments. During one run, reactor overpressurization resulted in a system shutdown, underlining the importance of reactor pressure control.

Scrubber system—The scrubber system is a key component in achieving acceptable emissions. Gases exiting the reactor first enter the spray tower leg for quenching, then pass to the packed tower. The scrubber removes residual organics, metals, particulates, and chlorides—cleaning the reformed gas.

Initially, as a result of incorrect installation of internal piping, the scrubber produced foam, affecting its efficiency. After ECO LOGIC modified the piping, the foaming stopped and the scrubber operated efficiently.

During processing, the pH meter did not perform satisfactorily because of radio frequency interference emanating from the recirculating heater spark plug wires. As a result, the addition of excess caustic contributed to the scrubber foaming. However, ECO LOGIC was able to manually measure and adjust the scrubber pH, preventing any program delays. This demonstrates the importance of relatively close scrubber pH control.

Recirculating fan—The 5-hp recirculating fan moved the scrubbed, recirculated, hydrogen-rich gas to the reactor inlet, the reformed gas to compression and storage, and a reformed gas slip stream to the boiler as supplementary fuel.

Scrubber foaming and water carryover caused excessive moisture in the fan casing. Eventually this condition required fan shutdown, cleaning, and motor winding replacement.

Boiler—The boiler provided clean steam to heat aqueous wastes in the heat exchanger and burned a portion of the reactor product—the reformed gas. Under normal operation, the boiler cycles between high fire and low fire, depending on process steam requirements. However, during Condition 1, Run 1, the boiler, operating at low fire, emitted high spike concentrations of THC and CO. Operation improved after ECO LOGIC adjusted the linkage controlling the air/fuel ratio to the boiler. However, during the remainder of the demonstration, ECO LOGIC vented steam to maintain boiler high-fire. Future design considerations should address the appropriate sizing of the boiler and control of fuel/air ratio to prevent excessive criteria pollutant emissions.

In Condition 3, the PCB-rich feedstock generated surplus reformed gas, more than the boiler could process. The boiler capacity, therefore, limited the system's throughput. To overcome this, ECO LOGIC added a compressed gas storage tank to the system. If, at the commercial scale, the process were operated as a fuel producer, the boiler would not restrict system throughput. In future operations, ECO LOGIC intends to compress and store the surplus reformed gas for sale and reuse. However, the remedial manager should address this report's earlier cautions concerning storage capacity and salability.

Liquid feed systems—The ECO LOGIC Reactor System had separate feed systems for organic liquid feed and aqueous liquid feed. The organic liquid feed system consisted of a feed tank and a feed pump. The aqueous liquid feed system consisted of a feed tank, a feed pump, and a heat exchanger. The aqueous liquid feed pump operated unstably, requiring frequent adjustment. ECO LOGIC should undertake further design work to improve the pump's reliability.

Process monitoring—The oxygen analyzer did not operate reliably. This is an important consideration since elevated levels of O₂ in the system can create an explosive atmosphere. Apparently, blockages in the analyzer sampling line caused the problem. Future configurations of this critical system should address this deficiency.

A differential pressure transmitter and a magnehelic gauge control the hydrogen content in the system, ensuring suffi-

Organics Destruction

To determine the efficiency of organics destruction, EPA evaluated DREs and DEs, benzene ring destruction, and formation of dioxins, furans, and other PICs.

DRE

DRE compares the mass flow rate of selected feedstock compounds—in this case PCBs—to their mass flow rate in the boiler stack gas.

$$\text{DRE (\%)} = (1 - \text{Mass}_{\text{stack}} / \text{Mass}_{\text{input}}) \times 100$$

Whenever possible, the evaluation based DRE calculations on actual detected values. When the value was below the detection limit for the method, input stream values were set at zero, while output streams were set at the detection limit value—the most conservative approach.

The ECO LOGIC Reactor Process achieved PCB destruction at the boiler stack ranging from 99.9999% to 99.99999%. This met established TSCA DRE requirements, potentially qualifying the process for use as a PCB treatment device. (Other TSCA requirements affecting residuals, stack emissions, and particulate emissions must also be considered.) The SITE Program results, supported by ECO LOGIC's laboratory-scale tests and results from their Hamilton Harbor Test (Appendix C) provide evidence of acceptable PCB destruction at the stack.

DE

DE is a measure of the system's ability to achieve organics destruction as measured around the system and all output streams.

$$\text{DE (\%)} = (1 - \text{Mass}_{\text{output}} / \text{Mass}_{\text{input}}) \times 100$$

PCE added to the feedstock acted as a tracer compound to calculate DEs; the system achieved the target objective—99.99%—for this tracer.

Benzene concentrations in the output streams were higher than expected. In scale-up, ECO LOGIC must address benzene concentrations in residual and effluent streams, since high benzene concentrations can affect the costs of waste disposal.

The DRE and DE results indicate that the ECO LOGIC Reactor System—with boiler—can achieve RCRA hazardous waste incinerator DEs (99.99% measured at the boiler stack) for most organic compounds. ECO LOGIC's lab-scale tests, their Hamilton Harbor test on sediment contaminated with PAHs (Appendix C), and the SITE Demonstration test of the ECO LOGIC TDU, discussed in an independent AAR, further support this conclusion. Assuming that scale-up factors maintain the same DE, a commercial-scale system would meet RCRA emissions criteria.

Dioxins and Furans

The ECO LOGIC Process reduces organics in a high-temperature hydrogen environment, as opposed to combustion by incineration in an oxygen environment. The absence of oxygen inhibits formation of polychlorinated dibenzo(p)dioxin/polychlorinated dibenzofuran (PCDD/PCDF). Although verifying the reduction mechanisms inside the reactor was not an objective of the demonstration, the test confirmed a net destruction at the stack of trace PCDD/PCDF in the feedstock. Stack emissions (corrected to 7% oxygen, dry basis) ranged from 0.156 to 0.368 ng/dscm dioxin and 0.007 to 0.011 ng/dscm furan—results well within incineration regulatory guidelines. The low PCDD/PCDF stack concentrations support the conclusion that the system can effect a net PCDD/PCDF destruction, resulting in PCDD/PCDF stack emission concentrations significantly lower than current limits.

PICs

"PICs" is an incineration term not directly applicable to the ECO LOGIC Process. The term describes a combustion system's ability to degrade feedstock organics. In a combustion system the final gaseous products are ideally water, carbon dioxide, and hydrogen chloride; other organic compounds are PICs. The ECO LOGIC Process products are more appropriately termed products of incomplete reduction (PIRs). The process generates both PIRs during the gas-phase reactions and PICs during the reformed gas combustion phase. Both terms are used here to facilitate comparisons between the emissions from combustion devices and those from the ECO LOGIC Process.

Incineration processes often select total hydrocarbons (THC), carbon monoxide (CO), total PAHs, and benzene as indicators of PIC/PIR formation. For the ECO LOGIC Reactor System tests, the three indicators—THC, CO, and total PAHs—were much lower than regulatory guidelines and well within the MDNR permit conditions. THC averages ranged from 1.53 to 15.5 ppmv, CO from 2.3 to 23.3 ppmv, and total PAHs from 24.0 to 28.6 µg/dscm (all corrected to 7% O₂, dry basis). The remedial manager can expect that the ECO LOGIC system will meet anticipated permit limits for THC, CO, and PAH emissions at other sites.

Benzene, ranging from 73 to 113 µg/dscm, exceeded both the MDNR permit guidelines and allowable air emission concentrations. A benzene ring balance, calculated at the stack, ranged from 80 to 96% DE. This DE did not reduce benzene concentrations to acceptable levels in the stack gas and scrubber effluent. Because benzene is a major intermediate product in the reduction of PAHs and PCBs, high benzene concentrations probably formed as these high molecular weight compounds degraded. Benzene is a by-product of the normal combustion process; this may have further increased stack emission concentrations. The remedial manager should closely monitor benzene levels.

Air Emissions

EPA evaluated emissions of criteria air pollutants and HCl, as well as compliance with the MDNR air permit.

Safety Considerations

The principal safety considerations for the ECO LOGIC Process concern personnel, chemical use, equipment integrity, and process control.

Personnel Safety

The components of personnel safety requiring attention are those associated with Construction Safety Standards [29 CFR 1926] addressing such topics as slips, trips, and falls; confined space entry; contingency planning; etc. The regulations in 29 CFR 1910.120 address PPE. High voltage electrical equipment standards are also a concern.

Chemical Use

The chemical hazards of the ECO LOGIC Process accompany the use of propane, liquified nitrogen/oxygen, hydrogen, industrial chemicals, and hazardous feed material. In addition, the process generates methane. Standardized industrial procedures provide guidance for storing, transporting, and handling these materials.

There should be no undue concern associated with hydrogen usage in the process. Well established and proven procedures are available for safe hydrogen storage and use. Hydrogen is no more nor less dangerous than gasoline or methane. As with these substances, hydrogen must be handled with due regard for its unique properties.

The electrical, petroleum refining, chemical, petrochemical, and synthetic fuel industries have safely used hydrogen in large quantities for decades. Through much of the last century Europe successfully used hydrogen-enriched gases (coal gas, town gas, producer gas) to satisfy residential fuel needs.² The Northeast United States used coal gas until the late 1950s.

For the demonstration, ECO LOGIC developed a Hydrogen Safety Procedure based on the *Canadian National Research Council's Safety Guide for Hydrogen*.² Ultimately, remedial managers must assure themselves that the flammable gases used in the ECO LOGIC Process are handled, stored, and used in accordance with industry standards and guidelines.

Equipment Integrity

Verification of system component integrity is essential to process safety. The remedial contractor should undertake pressure testing, hydrostatic testing, and metal embrittlement evaluations. The results should be certified before processing hazardous materials. Hydrogen is more difficult to contain than other gases because of its small molecular size. Therefore, interfaces of equipment, instruments, and piping must be leak-free. To provide an additional safeguard, ECO LOGIC maintains the system under slight positive pressure, preventing infiltration of oxygen. As a safety backup ECO LOGIC monitors internal oxygen levels and maintains gas feeds (propane and hydrogen) at low pressure to prevent pipeline breaks.

Process Safety System

ECO LOGIC designed a safety system to immediately react, should any system upset occur. The control system initiates system shutdown in response to high oxygen content, high pressure drop across the fan, scrubber pump failure, ground faults, boiler failure, high hydrocarbon emissions, or power failure. However, these shutdown systems were not needed during the demonstration.

Whenever process conditions require a system shutdown, the system program stops the waste input streams and replaces them with clean steam to prevent any negative pressure in the reactor. The program also stops hydrogen flow and introduces a nitrogen purge. Reformed gas flow to the boiler stops. Either an operator or an automatic computerized process controller initiates these events.

Staffing Issues

The CIMS facilitates monitoring and remote adjustment of process parameters. This reduces labor requirements for monitoring and maintenance personnel. The monitoring personnel must be capable of evaluating system problems and directing maintenance personnel in problem resolution. Since operations can be controlled remotely, only those personnel needing to manually adjust or maintain the system components require personal protective equipment. Since the system will be processing hazardous substances, the medical monitoring, training, and personal protection requirements of 29 CFR 1910.120 will remain in effect.

Regulatory Considerations

Several pieces of federal legislation and any state or local laws present compliance considerations in operating the ECO LOGIC Reactor System.

Clean Air Act

The Clean Air Act (CAA) establishes primary and secondary ambient air quality standards to protect public health; it also sets emission limits for hazardous air pollutants. Each state administers its own permitting requirements as part of the State Implementation Plan, developed to bring the state into compliance with National Ambient Air Quality Standards (NAAQS). These standards apply to the ECO LOGIC Process because of its potential emissions. The process will probably require an air permit to operate at any site, whether or not the state has attained its NAAQS. Even if the area is in attainment, prevention of significant deterioration regulations may further curtail emissions. Regulatory requirements must be determined on a site-by-site basis.

Clean Water Act

The Clean Water Act (CWA) regulates direct discharges to surface water through the National Pollutant Discharge Elimination System (NPDES). These regulations require that wastewater point-source discharges meet established water quality standards. The ECO LOGIC Process generates noncontact and contact water discharges. Noncontact water sources in-

restrictive stack concentrations. However, benzene emissions could potentially exceed permit levels at other sites. Scale-up designs should address these problems.

Intermediate and Residual Stream Characterization

Intermediate and residual stream evaluations provided process mass balance data; major effluent, intermediate process, and miscellaneous stream characterizations; and confirmation of adherence to TSCA permit conditions. Table 3 presents the mass distribution of the waste feed and effluent streams as fractions of the total waste feed. The waste oil was the major waste input stream, containing the greatest mass of PCBs. The major effluent streams were the stack gas and scrubber decant. Most of the material in these streams entered the process through combustion air and process water. Boiler combustion air contributed most of the mass to the stack gas stream; scrubber water, to the scrubber decant stream.

Table 4 shows the concentration of the major contaminants in the intermediate and effluent streams. These data indicate the tendency of contaminants to concentrate in the intermediate and residual streams.

Process Mass Balance

The test objectives included a system mass balance for metals, carbon, hydrogen, oxygen, sulfur, chlorine, and total mass. These balances were needed to evaluate system performance and to determine the fate of metals and other compounds in the feedstock.

The program established a value of $0 \pm 50\%$ (deviation from perfect closure) as the quality indicator (QI) of mass balance. Total mass balance closures ranged from -4.3 to +20.1%, indicating that data based on process mass balances (such as DRE, DE, and stack emission rates) can be considered very reliable. Carbon, chlorine, hydrogen, oxygen, and sulfur mass

balance closures ranged from -41 to +29.1%. Only the hydrogen in Condition 1 (-53.8%) and sulfur (+129%) and carbon (+98%) in Condition 3 exceeded the QI criterion. Therefore, the elemental mass balances further support DRE, DE, and partitioning data reliability. Closure of the metals balances, typically difficult to achieve in any system, ranged widely (from -153 to +175%). However, metal balance closures are of less concern than metals partitioning and their concentrations in residual streams.

Reactor Streams

The reactor system demonstration evaluated an intermediate stream—the reformed gas exiting the scrubber, and three major residual streams: reactor grit; scrubber residuals consisting of sludge, decant, and liquor; and stack gas emissions. It also analyzed miscellaneous streams, and compared the TSCA permit conditions to residual stream analyses. Stack gas emissions have already been discussed in the section on air emissions.

Intermediate Process Streams

Table 5 compares the reformed gas composition to several commercially available fuels. The scrubbed reformed gas was similar to blue water gas; its quality could be adequate to burn in suitable combustion equipment during commercial-scale operations. Use of the reformed gas in cogeneration or other equipment to support the remedial operation could improve the economics of large-scale applications. Although the reformed gas was of commercial quality, it would be a specialty fuel requiring burners tailored to its properties. Compressing and storing the reformed gas for resale or future use would probably be uneconomical. Unlike propane, the compressed reformed gas needs cryogenic temperatures to liquify. Therefore, storage as a gas would require excessively large tanks.

Residual principal organic hazardous constituents (POHCs) and PIRs may affect the end use of the gas. As previously discussed, PCB DEs measured for the scrubbed reformed gas were essentially equal to the DEs measured at the boiler stack. This was also true for the PCE DEs, with the exception of two Condition 3 runs. The measured PCE DE in the reformed gas was an order of magnitude lower than that measured at the boiler stack. Run 1 and Run 3 achieved 99.988% and 99.97% DEs of PCE in the reformed gas, slightly below the 99.99% target level for this tracer compound. The DE levels demonstrated for the chlorinated organic compounds indicate that a commercial-scale system can achieve consistent DEs of 99.99%.

Benzene was the most prevalent PIR in the reformed gas. Benzene concentrations ranged between 522 and 1,780 mg/dscm. PAHs were not measured. However, as shown in Table 4, the combustion step in the boiler destroys most of the residual benzene. PAH emissions from the boiler stack also were low. The reformed gas is generated from a hazardous waste, presenting a further difficulty in its utilization as a fuel outside of the process. However, the results of the demonstration show that burning the reformed gas in combustion equipment would adequately destroy any residual hazardous organics.

Table 3. Mass Distribution of Selected Streams

Stream		Material quantity*	
		Condition 1	Condition 3
Input			
Wastewater	SS1	0.984	0.781
Waste oil	SS2	0.016	0.219
Residual/output			
Reactor grit	SS11	0.001	0.001
Scrubber sludge	SS12	0.032	0.172
Scrubber decant	SS13	1.097	3.659
Scrubber liquor	SS22	0.122	0.005
Compressed tank condensate	SS15	N/A	0.002
Stack gas	SS16	0.738	0.980

*kg material per kg total feed.

Section 4

Economic Analysis

Introduction

Estimating the cost of employing an innovative technology is a major objective in each SITE demonstration project. This economic analysis presents data on the costs (excluding profit) for a commercial-scale remediation using the ECO LOGIC Gas-Phase Chemical Reduction Process. With a realistic understanding of the test costs, it should be possible to forecast the economics of operating similarly sized systems or to extrapolate these figures for larger systems at other sites.

The SITE Demonstration of the ECO LOGIC Reactor System conducted at the Middleground Landfill treated both PCB-contaminated wastewater and waste oil. This economic analysis is an extrapolation of that experience based on the commercial use of a system similar to that employed during the demonstration program. For the purposes of this analysis it was assumed that 100,000 gallons of wastewater and 30,000 gallons of waste oil were stockpiled for treatment. The waste streams are assumed to be identical in composition to those treated during the demonstration program. The following feedrates were utilized for this analysis: 1.73 kg/min of wastewater and 0.485 kg/min of waste oil, simultaneously injected into the reactor. Since the process could experience some downtime, a sensitivity analysis presents three different on-line utilization factors: 60%, 70%, and 80%. Certain cost elements were fixed; others were time-sensitive.

Decreased process efficiency (lower utilization factor) would require an extended time to process the same amount of material, reflecting higher costs. Final figures have been expressed as cost (U.S. dollars per ton) of material processed.

Conclusions

The data showed the ECO LOGIC Reactor Process to be an acceptable remedial alternative for liquids contaminated with PCBs. Since the process was effective in treating the PCB-contaminated Middleground Landfill liquids, it should be applicable to the remediation of other similar sites.

The treatment costs (1994 U.S. dollars) ranged from a low of \$1,670/ton to a high of \$2,000/ton, depending on the utilization factor. Because of limited data, the cost estimates presented in this analysis may range in accuracy from +50% to -

30%, an order of magnitude guideline suggested by the American Association of Cost Engineers.

Issues and Assumptions

The costs associated with this technology were calculated on the basis of demonstration parameters such as the following:

- A small to medium hazardous waste site
- Three tons of liquid feed
- A short treatment period during the SITE Demonstration

While the equipment used for the demonstration was a small commercial size, it may not be applicable where time constraints require increased capacity. The targeted test throughput rates were considerably higher than those actually realized during the demonstration. Variations in throughput could significantly affect costs.

Important assumptions regarding specific operating conditions and task responsibilities, described below, will impact cost estimates.

Site-Specific Factors

The demonstration site presented certain site-specific characteristics that affected the cost estimate. Variations to these site-specific characteristics may improve or worsen the project economics:

- Proximity to utilities, with capacity sufficient to service project
- Favorable ambient conditions
- Clear, level work area
- Small, specialized project with minimal requirements for storage, administration, services, etc.

Fixed costs are not related to time or volume; nor are they affected by project magnitude. Such costs include the transportation/setup/removal of trailers, sanitary facilities, decontamination facilities, process equipment, foundations, roads, and utilities. In employing the results of this SITE economic analysis to forecast a unit cost (dollars/ton), the potential user should recognize that these same fixed costs spread over larger volumes of contaminated material would lower the unit cost. The reverse would be true of a smaller project.

Table 5. Reformed Gas Comparison to Other Fuels

Gaseous Fuels		Composition, percent by volume							
		H ₂	N ₂	O ₂	CH ₄	CO	CO ₂	C ₂ H ₄	C ₆ H ₆
ECO LOGIC reformed gas	Condition 1	41.1	33.7	0.05	12.2	5.1	6.7	0.4	—
	Condition 3	55.7	13.7	0.06	16.9	8.0	3.3	0.7	—
Blast furnace gas		1.0	60.0	—	—	27.5	11.5	—	—
Blue water gas		47.3	8.3	0.7	1.3	37.0	5.4	—	—
Carburated water gas		40.5	2.9	0.5	10.2	34.0	3.0	6.1	2.8
Coal gas		54.6	4.4	0.2	24.2	10.9	3.0	1.5	1.3
Coke-oven gas		46.5	8.1	0.8	32.1	6.3	2.2	3.5	0.5
Natural gas (15.8% C ₂ H ₆)		—	0.8	—	83.4	—	—	—	—
Producer gas		14.0	50.9	0.6	3.0	28.0	4.5	—	—

Gaseous Fuels		MW	HHV Btu/lbm	HHV Btu/scf	Sp. gr. air = 1.0
ECO LOGIC reformed Gas	Condition 1	16.7	6,250	269	0.58
	Condition 3	11.6	12,610	376	0.54
Blast furnace gas		29.6	1,170	89	1.02
Blue water gas		16.4	6,550	277	0.57
Carburated water gas		18.3	11,350	535	0.63
Coal gas		12.1	16,500	514	0.42
Coke-oven gas		13.7	17,100	603	0.47
Natural gas (15.8% C ₂ H ₆)		18.3	24,100	1,136	0.63
Producer gas		24.7	2,470	157	0.85

MW Molecular weight
HHV Higher heating value
Sp. gr. specific gravity compared to air at 60°F

The grit also contained PAH levels exceeding 846 ppm, benzene levels up to 17 ppm, and PCDD/PCDF reaching 0.162 ppm. Chlorobenzenes, chlorophenols, and PCE were not detected.

Scrubber Residuals—The scrubber is a critical component in the gas-phase chemical reduction process. The scrubber effectively removes a variety of organic and metallic compounds, particulates, and chlorides. It is a key element in achieving DREs. Table 4 shows elevated levels of hazardous organic compounds in the scrubber sludge—mainly PAHs, with lesser concentrations of PCBs and PCDD/PCDF. If this sludge is not recycled through the process, it must be treated as a TSCA and RCRA hazardous waste.

Based on detected PCB congeners, the PCB concentrations in the scrubber decant (40.6 to 203 ppb total) and scrubber liquor streams (31.5 to 48.9 ppb total) met the TSCA criterion of less than 3 ppb per PCB congener in liquid residuals. For the demonstration, these streams were combined in a storage tank. Subsequent sampling by TSCA personnel confirmed that the stored liquids met the 3 ppb TSCA criterion.

If monochlorobiphenyls, dichlorobiphenyls, and nondetected congeners (assumed to be present at the detection level) are included, the scrubber decant could contain maximum PCB concentrations of 203 ppb; the scrubber liquor could contain PCB concentrations up to 48.9. If these streams are not

recycled through the process, they will require further treatment as a RCRA waste.

The scrubber residuals did not contain detectable levels of chlorobenzene and chlorophenols. In Condition 3, PCE was detected at very low levels in the scrubber decant and scrubber liquor, but not in the sludge.

The absence of chlorobenzene, chlorophenols, and the relative absence of PCE in the residual streams downstream of the reactor provide further evidence that the ECO LOGIC Process effectively removes chlorine from chlorinated organic compounds. PAHs were the principal organic compounds detected in the residue; benzene occurred in elevated concentrations in the residual streams. The benzene and PAHs are most likely PIRs resulting from the dechlorination of the PCBs. Also, residual PCB concentrations and PCDD/PCDF concentrations, although low, were present in all residue streams. The remedial manager should evaluate concentrations of these compounds at other sites, as they will likely be found at detectable levels.

Miscellaneous Streams

The demonstration team collected water that came in contact with the processing equipment—such as wash and rinse water from equipment decontamination—and stored it apart from other wastes, disposing of it as a hazardous waste. The treatment/disposal of this wash/rinse water is site-specific.

Table 8. Operating Labor*

Category	Hire	Number	Shifts	Hr/wk	All-in cost/hr	Total per week
Engineering	Direct	1	1	40	\$40.00	\$1,600
Shift supervisor	Local	1	4	160	34.00	5,440
Technicians	Local	2**	4	280	30.00	8,400
Clerk (part-time)	Local	1	1	20	20.00	400
Subtotal						15,840
Time/labor for engineer						760
Total per week						\$16,600

* 24 hours per day, 7 days per week operation.

** 4 shifts (shift 3 - only 1 technician).

Table 9. Labor Costs Based on Utilization

Utilization (%)	Cost/week	Weeks	Labor cost
60	\$16,600	34	\$564,400
70	16,600	30	498,000
80	16,600	26	431,600

Despite the fact that most of these activities are site-specific, they represent a typical percentage of the overall cost that can be expected on any project. Therefore, they have been included in the cost analysis.

The analysis excluded site engineering, work plan preparation, and pretreatment of hazardous waste feed. Table 10 lists the cost elements associated with site preparation for the ECO LOGIC SITE Demonstration.

Permitting and Regulatory Costs

Permitting and regulatory costs are generally the obligation of the responsible party or site owner. These costs may cover actual permit application, monitoring, and the development of monitoring and analytical protocols. Permitting and regulatory costs vary greatly because they are specific to the site, waste, and technology. Therefore, no permitting and regulatory costs have been included in this analysis. Depending on the treatment site, however, they could be a significant factor, since such activities can be both expensive and time-consuming.

Capital Equipment

This cost category includes all equipment provided by the technology developer; it generally encompasses equipment integral to the process. For this analysis, holding tanks and incidental equipment have been relegated to other categories.

Table 11 provides a breakdown of the reactor capital equipment costs. Comparable costs associated with the TDU/reactor combination are addressed in the complementary TDU AAR.

Prices for the various pieces of equipment were obtained from vendor catalogs, Richardson's cost estimating handbooks, and

Table 10. Demonstration Site Preparation Costs

Item	Description	Cost
1	Site fencing (chain link)	\$2,500
2	Snow fencing (wood)	100
3	Access roads	12,000
4	Gravel and stone	2,000
5	Concrete pads	4,500
6	HDPE liner	3,500
7	Temporary piping	1,300
8	Temporary electric	2,000
9	Telephone	500
10	Sump pumps	1,000
11	Security	8,000
12	Signs, etc.	1,000
13	Personal protective equipment	2,000
14	Engineering support	5,000
15	Administrative support	5,000
16	Site supervision	60,000
17	Travel and living	12,000
18	Miscellaneous	5,000
Total		\$127,400

historical data. General specifications were provided by the developer. The figures excluded all research and development costs. No license fees or royalties have been included.

In terms of size and throughput capacity, the actual equipment used for the demonstration was also used for the analysis.

The operational duration of the project in the forecast is less than 1 year. Therefore, the equipment costs have been annualized based on the following formula:

$$A = C \frac{i(1+i)^n}{(1+i)^n - 1}$$

A = annualized cost, \$

C = capitalized cost, \$

i = interest rate, 6%

n = useful life, 10 years

cient hydrogen to reduce (destroy) the organics. Insufficient hydrogen content can slow the reaction kinetics, causing incomplete reduction. During the demonstration, the lines to the pressure sensors plugged, resulting in an insufficient hydrogen content and generating oily residue that coated equipment and instrumentation, further affecting system operations. ECO LOGIC should consider a design change to improve instrument reliability.

System Reliability

The program evaluated system reliability during processing and during a 72-hour uninterrupted test. The reliability has been expressed in terms of planned availability compared to actual on-line availability. The number of days planned for the entire demonstration was 10 (reactor and TDU/reactor tests); the program actually took 42. This translates to a 24% equipment availability.

In addition, the program evaluated actual waste throughput as a percent of the planned input—a throughput reliability. The wastewater test was designed to treat 8 tons of material, but processed 2.9 tons. The waste oil test nearly achieved the planned throughput of 0.8 tons. The resulting throughput reliability percentages varied between 20% and 55% over the six runs. However, during the 72-hour continuous operation using liquid feedstock, the system operated without interruption.

Scale-up Parameters

One program objective sought to identify the critical scale-up parameters. Knowing these parameters assists future users in evaluating a proposed commercial-size operation. This report has addressed scale-up considerations as they pertain to the immediate discussion.

CIMS Validation

The CIMS is the primary process control unit of the ECO LOGIC Process. It records and stores data. It measures selected compounds and their decomposition products to maximize organic destruction.

Demonstration results show that the CIMS may reflect data trends useful for process control, but it is not, at this stage of its development, a reliable source of quantitative data. Further testing will determine whether the CIMS can provide adequate process control.

System Operating Conditions

Automatic computer data and manual logs documented process operating conditions and the status of the operating components. These data clarified process results and documented compliance with permit conditions. Table 6 lists the averages for several key system parameters; the TER contains further details.

Table 6. Summary of Reactor Operating Conditions

Equipment	Parameter	Test condition averages	
		1	3
Reactor	Temperature (°C)	892	933
	Pressure (in. H ₂ O)	1.8	1.8
	Residence time (sec)	8	6.1
Scrubber	Inlet temperature (°C)	546	527
	Outlet temperature (°C)	33	32
	Water pH	8.78	9.32
Recirculating fan	Differential pressure (in. H ₂ O)	11.6	7.8
	Flow rate (cfm)	110	110
	Gas pressure (in. H ₂ O)	6.5	0.66
Vaporizer	Temperature (°C)	148.3	149
	Pressure (psi)	51.8	51.4

Technology Applicability

This section describes the applicability of the technology to the site, waste media, safety, and staffing.

Site Characteristics

The ECO LOGIC system requires a fairly level area, approximately 120 ft x 180 ft, for the processing and auxiliary equipment. Utility tanks require level surfaces or supports. Except for process gas tank support pads, no additional surface support is needed. The reactor system sits on two mobile trailers.

Cold-weather operations may inhibit efficient destruction because of the incremental amount of energy required to heat the reactor. In addition, feedstock liquids would require melting prior to treatment, and liquid residuals could freeze in the unheated storage tanks. Winterization, including heat tracing, is necessary to provide adequate feedstock and to ensure uninterrupted processing.

Applicable Media

Initially, ECO LOGIC designed the reactor system to process liquids, with soil processing limited to about 30% solids¹. ECO LOGIC added the TDU to gain greater feedstock processing capabilities. As explained in an independent AAR, the demonstration indicated that the TDU requires further development.

The reactor system is best suited for processing liquids and TDU off-gases/water vapor. The waste's organic content limits the demonstration-scale system's feed rate because of reformed gas generation. Currently, ECO LOGIC plans to improve throughput by storing excess reformed gas after compressing it. Future users should consider the implications, logistics, and costs of this approach.

Table 12. Mobilization/Start-Up Costs

Description	Cost/Month (\$)	Utilization		
		60%	70%	80%
Fixed costs				
Delivery/blocking trailers		\$1,550	\$1,550	\$1,550
Trailer furnishings		2,000	2,000	2,000
Hooking up process equipment		15,000	15,000	15,000
Storage tanks and vessels		11,000	11,000	11,000
Drums and pails		2,600	2,600	2,600
Crane rentals, etc.		1,400	1,400	1,400
Monthly costs				
Trailers (5)	500	\$4,000	\$3,500	\$3,000
Portable toilets (2)	150	1,200	1,050	900
Dumpsters	150	1,200	1,050	900
Job vehicles	1,000	8,000	7,000	6,000

Table 13. Cost Allocations

Description	Utilization		
	60%	70%	80%
Transportation	\$1,000	\$1,000	\$1,000
Working capital	9,000	9,000	9,000
Insurance	32,000	28,000	24,000
Start-up (4,000)	20,000	20,000	20,000

Repairs and Maintenance

Maintenance labor and material costs vary with the nature of the waste, the performance of the equipment, and the site conditions. For estimating purposes, roughly \$500/mo has been allowed. This represents approximately 10% of capital equipment.

The key maintenance items associated with the ECO LOGIC Process are the electrically heated bars in the reactor. The anticipated life span, under the operating conditions described, has not yet been defined.

Demobilization

Demobilization costs were limited to disassembly, site cleanup, and limited restoration. Disassembly covered the following: disconnection of equipment and utilities, surface decontamination (for transportation off-site) of all process equipment, and loading. Transportation to the next destination was not included.

Site restoration included the removal of all utilities, trailers, and rental equipment. Requirements regarding permanent fencing, grading, landscaping, etc., vary by site. Depending on the future use of the site, they were assumed to be the obligation of the site owner or the responsible party. They were not included in this analysis.

Results of Economic Analysis

Table 14 presents the total treatment cost for the reactor system. The table was organized in accordance with the 12 EPA cost categories. In addition to total treatment costs, a unit cost (dollars/ton) has been provided. In an effort to address unforeseen job conditions, a range of costs for 60%, 70%, and 80% utilization factors has been calculated.

The largest single cost component of this treatment technology was operational labor—accounting for 52% of the total treatment cost at 80% utilization. Supplies accounted for 12% of the total, while site preparation made up 15%, and mobilization/start-up, 12%. The remaining eight categories comprised only 9% of the total treatment cost, with three having no cost associated with them for this SITE project analysis.

Considering the effect of the labor component on price and the relative constancy in scale-up of the other components, it is likely that unit costs would benefit significantly from commercial scale-up. Increasing equipment capacity would decrease process time and labor cost.

Table 15 compares the costs per ton for the actual test throughputs with the costs estimated for targeted throughputs. If targeted throughputs had been achieved, costs per ton would have been substantially lower. A commercial-scale unit would further decrease these figures.

References

1. Richardson Engineering Services. *Cost Estimating Guide*, Vol 1, 1993 edition.
2. R. S. Means. "General Building Construction," *Cost Estimating Services*.
3. Evans, G. M. "Estimating Innovative Technology Costs for the SITE Program." EPA/RREL for *Journal of Air Waste Management Association*. July, 1990. Volume 40, No. 7.

clude the heat exchanger, evaporative cooler, boiler water, and blow-down. Contact water comes from the TDU quench, scrubber liquor, tank cleaning, and equipment wash down; it will likely require further treatment prior to discharge to a POTW. In any case, wastewater discharge to a sanitary sewer requires a discharge permit or, at least, concurrence from state and local regulatory authorities that the wastewater is in compliance with regulatory limits.

Comprehensive Environmental Response, Compensation, and Liability Act

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, amended by SARA of 1986, provides federal funding to respond to releases of hazardous substances to air, water, and land. Section 121 of SARA, entitled "Cleanup Standards," states a strong statutory preference for remedies that are highly reliable and provide long-term protection. It recommends that remedial action utilize on-site treatment that "... permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances." In addition, remedial actions must consider the technology's long-term and short-term effectiveness, implementability, and cost.

The ECO LOGIC Reactor Process satisfies the SARA mandate to reduce the toxicity, mobility, and volume of hazardous substances by reducing organic contaminants in the feedstock—such as PCBs—to lighter, nontoxic hydrocarbons, such as methane and ethylene. The demonstration showed that the reactor system destroyed more than 99.99% (DE) of the contaminants, illustrating both long-term and short-term effectiveness with respect to organic compounds. It indicated that metals were mainly concentrated in the scrubber effluent, which required additional treatment prior to disposal. EPA cost estimates are found in Section 4.

The system appears implementable as currently designed. Relatively mobile, it requires water and electric utilities; hydrogen, oxygen, nitrogen, and propane storage; and front-end material handling equipment to deliver feedstock to the feed storage tanks.

Occupational Safety and Health Act

Sections 1900 to 1926 of the Occupational Safety and Health Act (OSHA) govern ECO LOGIC remedial operations: 1910.120 for hazardous waste operations, 1926 for construction site activities, and 1910.1200 for worker and community right-to-know.

Resource Conservation and Recovery Act

RCRA is the primary federal legislation governing hazardous waste activities. RCRA Subtitle C contains requirements for generation, transport, treatment, storage, and disposal of hazardous waste, most of which are applicable to CERCLA activities.

Depending on the specific waste feed and the effectiveness of the treatment, the ECO LOGIC Reactor Process generates two

potentially hazardous waste streams: the scrubber liquor and the treated soil. To generate these wastes, the remedial manager must obtain an EPA generator identification number and either comply with generator accumulation and storage requirements under 40 CFR 262, or receive a Part B Treatment, Storage, and Disposal (TSD) interim status permit. CERCLA mandates compliance with RCRA TSD requirements. A hazardous waste manifest must accompany off-site waste shipment; transport must comply with Federal Department of Transportation (DOT) hazardous waste transportation regulations. The receiving TSD facility must hold a permit and comply with RCRA standards.

Technology or treatment standards apply to many hazardous wastes; those appropriate for the ECO LOGIC Process depend on the waste generated. RCRA land disposal restrictions, 40 CFR 268, mandate hazardous waste treatment after removal from a contaminated site and prior to land disposal, unless a variance has been granted. The scrubber liquor and treated soil will require additional treatment prior to land disposal if they do not meet their pertinent treatment standards.

Toxic Substances Control Act

The ECO LOGIC Process treats wastes containing PCBs. Therefore, the remedial manager must address TSCA standards for PCB spill cleanups and disposal. The EPA document, *CERCLA Compliance with Other Laws Manual*,³ discusses TSCA as it pertains to Superfund actions.

If ECO LOGIC plans to treat PCB-contaminated material containing no RCRA wastes, they must obtain a TSCA authorization. The conditions of this authorization may contain operational, throughput, or disposal constraints that could affect treatment efficiency and costs. If ECO LOGIC chooses to treat PCB-contaminated material containing RCRA wastes, a RCRA permit for a TSD facility will also be required.

State and Local Regulations

Compliance with applicable or relevant and appropriate requirements may require meeting state standards that are more stringent than federal standards; state standards may control non-CERCLA treatment activities. Several types of state and local regulations affect operation of the ECO LOGIC Process, such as, permitting requirements for construction/operation, prohibitions on emission levels, and nuisance rules.

References

1. U.S. Office of Technology Assessment, "Dioxin Treatment Technologies" (background paper), OTA-BP-0-93, U.S. Government Printing Office, Washington, D.C., November 1991.
2. Kalyanam, K. M., and Hay, D. R., *Safety Guide for Hydrogen*, National Research Council of Canada, Ottawa, Ontario, 1987.
3. U.S. EPA. *CERCLA Compliance with Other Laws Manual Part II: Clean Air Act and Other Environmental Statutes and State Requirements, Interim Final*, EPA/540/G-89/009, OSWER, Washington, D.C., August 1989.

Appendix A

Demonstration Sampling and Analysis

Introduction

The ECO LOGIC Reactor System SITE Demonstration consisted of two test conditions with three runs each. Condition 1 treated PCB-contaminated wastewater; Condition 3, PCB-contaminated waste oil. The TDU demonstration comprising Condition 2 processed contaminated soil—the subject of an independent AAR.

Sampling and analysis of the feedstock, intermediate streams, and residuals followed the procedures outlined in the demonstration plan. EPA subjected the entire sampling and analysis program to a rigorous Category II Quality Assurance (QA) procedure designed to generate reliable test data. The demonstration plan also contains the QA procedure. The TER presents a detailed account of the demonstration results.

Figure A-1 shows the sampling locations. An SS designation represents EPA contractor sampling locations shown in Table A-1; MS indicates an ECO LOGIC Process monitoring station, listed in Table A-2.

Methodologies

The EPA program sampled three matrices: gases, liquids, and solids. EPA sampled and analyzed all key input and output streams; they selected intermediate streams for physical properties (flow rate, density, moisture), PCBs, PCDD/PCDF, PAHs, PCE, chlorobenzenes, chlorophenols, volatile organic compounds (VOCs), 13 trace metals, HCl, O₂, CO₂, CO, SO₂, NO_x, THC, and other selected compounds. Tables A-3, A-4, and A-5 list the sampling and analysis methods used by EPA. The demonstration plan and TER contain further details about the Sampling and Analysis Program.

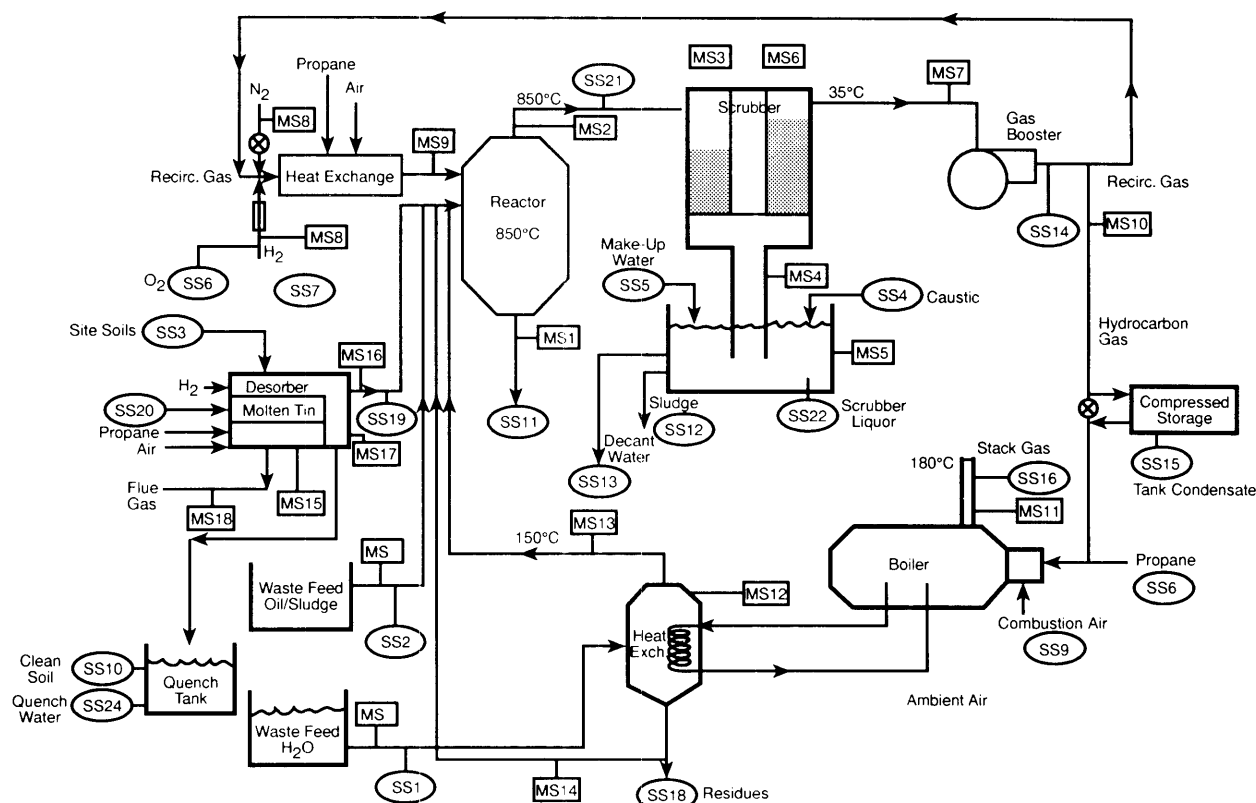


Figure A-1. Sampling and monitoring stations.

Costs Excluded from the Estimate

Although the SITE Program provides a 12-item list of costs on which the economic analysis of a demonstration should be calculated, not all 12 apply to every project. Certain cost items were excluded from this analysis because they were either site-specific, project-specific, or the obligation of the site owner/responsible party.

Utilities

Electrical power was required for the operation of the various pumps, blowers, feeders/conveyors, and electric heating elements, in addition to instrumentation, lighting, and miscellaneous power outlets. The total system demand at full efficiency averaged 30 kW.

Scrubber make-up water requirements were minimal; actual volume used was not available. For calculations, the addition of 178 kg/hr of water (about 50 gal/hr) was assumed.

The recirculating gas heat exchanger and boiler needed a natural gas source along with required piping and appurtenances. During the demonstration, propane fuel was used. For Condition 1, the propane consumption rate was 7.62 kg/hr; for Condition 3, 12.9 kg/hr.

With the exception of propane, the analysis assumed that all utilities, in appropriate capacities, were available at the site.

Supplies

Table 7 shows the types and quantities of consumable supplies required by the ECO LOGIC Reactor Process.

Operating Conditions

This analysis assumed that the facility would operate 24 hours a day, seven days a week. At the throughput rates discussed earlier, the required operating times were calculated with the three different utilization factors, as follows:

250 days (60% utilization)
214 days (70% utilization)
188 days (80% utilization)

These periods excluded mobilization, shakedown, start-up, and demobilization times.

Table 7 Consumables Required by the ECO LOGIC Reactor Process

Item	Measure	Condition 1 (Water)	Condition 3 (Oil)
Caustic	kg/hr	24.7	116.7
Hydrogen	kg/hr	0.138	0.072
Propane	kg/hr	7.62	12.9
Nitrogen	m ³	15	15

Labor

Four crews, consisting of a shift supervisor and two technicians, would provide coverage for a 24-hour, seven-day, three-shift reactor operation. The project engineer/manager would work Monday to Friday during the day shift; a part-time clerk, the same schedule. The first and second shifts would require two technicians. The third shift (midnight to 8:00 am) would require only one.

The Project Engineer/Manager would hire all non-union local workers. Table 8 lists the labor classification, number of workers, and unit labor rates used in the forecasts. Table 9 shows the data totals based on utilization percentage.

The estimates excluded costs for OSHA training time, medical screening for all personnel on-site, and operations training.

Basis for Economic Analysis

To provide a basis of cost-effectiveness comparison among technologies, the SITE Program links costs to 12 standard categories, listed below:

- Site preparation
- Permitting and regulatory
- Capital equipment
- Mobilization and start-up
- Operations labor
- Supplies
- Utilities
- Effluents
- Residuals
- Analytical
- Repair and maintenance
- Demobilization

Some of the cost categories above do not apply to this analysis because they are site-specific, project-specific, or the obligation of site owner/responsible party:

- Project engineering and design, specifications, requisitions
- Permits, regulatory requirements, plans
- Wells, pipelines, excavation/stockpiling/handling of waste (except for feed to process equipment),
- Backfilling, landscaping, any major site restoration
- Sampling and chemical analysis except as required for disposal of miscellaneous effluents and wastes
- Initiation of monitoring programs
- Post-treatment reports, regulatory compliance

Wherever possible, applicable information has been provided on these excluded costs so that potential users may calculate site-specific economic data for their particular projects.

Site Preparation Costs

The extent of preparation depends on the specific site characteristics. Such activities include site design, layout, surveys, acquisition of access rights, establishment of support and decontamination facilities, and utility connections.

Table A-3. Flue Gas Sampling and Analytical Methods

Analyte	Sampling Principle	Reference	Analytical Principle	Reference
PCBs	XAD-2	Method 0010*	HR GC/HR MS	EPA 680*
Dioxins/furans	XAD-2	Method 0010	HR GC/HR MS	EPA 23**
PAHs	XAD-2	Method 0010	GC/MS	EPA 8270*
CB/CP	XAD-2	Method 0010*	GC/MS	EPA 8270*
Volatile organics	Tenax	Method 0030*	GC/MS	EPA 5041*
Metals	Impinger	EPA Method 29 (draft)	CVAAS, ICAP, GFAAS	EPA 29 (draft)
HCl	Impinger	EPA Method 26**	IC	EPA 26**
Particulates	Filter	EPA Method 5**	Gravimetric	EPA 5**
NO _x	CEMS	EPA Method 7E**	Chemiluminescence	EPA 7E**
SO ₂	CEMS	EPA Method 6C**	NDUV	EPA 6C**
O ₂	CEMS	EPA Method 3A**	Paramagnetic	EPA 3A**
CO ₂	CEMS	EPA Method 3A**	NDIR	EPA 3A**
CO	CEMS	EPA Method 10**	NDIR	EPA 10**
THC	CEMS	EPA Method 25A**	FID	EPA 25A**
Fixed gases	Tedlar bag	EPA Method 18**	GC	MASA 133***
Sulfur compounds	Tedlar bag	EPA Method 18**	GC/FPD	EPA 15**
Heating value	Tedlar bag	EPA Method 18**	GC	ASTM 2620M

* *Test Methods for Evaluating Solid Wastes*, SW-846, U.S. EPA (November 1986, reissued July 1992 and November 1992).

** *Code of Federal Regulations*, 40 CFR 60.

*** Lodge, J.P., *Methods of Air Sampling and Analysis*, 3rd Edition, Lewis Publishers, Inc., Chelsea, MI, 1989.

Table A-4. Solids Sampling and Analytical Methods*

Analyte	Analytical Principle	Reference
PCBs	GC/MS	EPA 680*
Dioxins/furans	HR GC/HR MS	EPA 8290*
CB/CP	GC/MS	EPA 8270*
PAHs	GC/MS	EPA 8270*
Volatile organics	GC/MS	EPA 8260*
Metals	CVAAS, AAS, ICAP	EPA 6010, 7471*
Organic halogens	IC	EPA 9020*
Inorganic halogens	IC	ASTM E776
Hexavalent chromium	Colorimetric	EPA 7196*
Total sulfur	Gravimetric	ASTM D3177
TCLP volatiles	GC/MS	EPA 8240*
TCLP metals	CVAAS, ICAP	EPA 6010, 7470*
Ash	Combustion/gravimetric	ASTM D482
Heating value	Bomb calorimeter	ASTM D240
Ultimate analysis	Combustion	ASTM D3176
Total organic carbon	GC	EPA 9060*
Density	Hydrometer	ASTM D1298

* Using grab samples, performed in accordance with U.S. EPA Office of Solid Waste document *Test Methods for Evaluating Solid Wastes*, SW-846, 3rd Edition, Volume II, Chapter 9, November 1986.

Table 11. Capital Equipment for Commercial Operation

Item	Description	Total
1	Reductive heater	\$20,000
2	Heat exchangers (2)	60,000
3	Reactor	74,000
4	Scrubber	36,000
5	Recirculating fan	10,000
6	Gas storage vessel	10,000
7	Boiler	113,000
8	Pumps	19,000
9	Sludge/oil tank	10,000
10	Wastewater tank	10,000
11	Lowboy trailers	55,000
12	Ductwork	5,000
13	Electrical system	21,000
14	Control system	40,000
15	Miscellaneous pipes and valves	32,000
16	Miscellaneous structures and supports	5,000
17	Instrumentation	32,000
18	Electrical bulks	11,000
19	Miscellaneous process items	22,000
Total		\$585,000

Mobilization and Start-up

Mobilization includes the setup of the work site including trailers, utilities, and miscellaneous materials, as well as the transportation and assembly of the process equipment. Table 12 breaks down the significant cost items associated with this category.

Transportation costs were calculated on the basis of 500 one-way road miles at an average of \$2.00 per mile. One-way miles were used because it was assumed that the equipment travels from active site to active site.

The process equipment consisted of two pre-assembled flat-bed trailers. A separate allowance covered final hook-up at the site, while shakedown costs comprised part of the allowance for start-up (Table 13).

Transportation costs for personnel have been included in the **Labor** category.

Taxes and insurance were calculated as 5% of capital equipment. An allowance for working capital, equivalent to approximately one month's inventory of supplies, has been included (\$9,000).

Start-up costs included labor for a five-man crew during one 60-hour week, plus an allowance for consumables and miscellaneous. The cost analysis did not provide for a separate contingency; however, start-up costs included a 10% contingency.

Operations Labor

Personnel requirements for operating the facility under various conditions have already been discussed. They included wages and travel expenses for on-site operations personnel. Fully burdened wage rates were shown by labor category in Table 8. It was assumed that all personnel would be local hires except the project engineer/manager. Per diem for the project manager—lodging, food, and rental car for a seven-day-week—has been calculated at \$110/day.

Supplies

This cost category, consisting of chemicals and fuels, was based on consumption rates for the various operating conditions. Northeastern area vendors provided verbal quotes with no consideration for large bulk quantity or unusual transportation. (Chemicals and fuels could be purchased locally for approximately the same price.)

Supplies also encompassed disposable personal protective equipment (PPE) for Level D. The category also included a \$5,000 allowance for unspecified consumables and spares.

Utilities

Electrical usage, make-up water consumption, and telephone charges comprised the utilities category. Electrical demand in kilowatt hours was extrapolated from actual demonstration experience at \$0.08/kWh. Make-up water was calculated at approximately 50 gal/day and \$0.05/gal. Telephone charges were set at \$300/month.

All utilities were assumed to be available at the site. However, costs excluded installation, hook-up, etc., which were covered under **Mobilization**.

Effluents

There were no costs associated with effluents in this analysis since no material would be introduced into normal effluent streams.

Residuals

Residuals generated by this process would include grit and fines that would be stored in drums and transported to an approved disposal site. This category also included the transportation and disposal of PPE stored in drums. The process generated approximately 0.071 kg/hr of grit, slightly more than 500 lbs for this application.

Analytical

No analytical costs have been included in this cost estimate. The client could elect (or might be required by local authorities) to initiate a sampling and analytical program to meet local regulatory criteria. These analytical requirements could significantly affect costs.

Appendix B

Vendor's Claims

Introduction

Following the 1992 SITE Demonstration of the ECO LOGIC Gas-Phase Chemical Reduction Process in Bay City, Michigan, several advancements have been made. Further research and development has focused on optimizing the process for commercial operations, and improving the design of the soil/sediment processing unit. These advances along with relevant background information are described herein.

Since 1986, ECO LOGIC has been conducting research with the aim of developing a new technology for destroying aqueous organic wastes, such as contaminated harbor sediments, landfill soil and leachates, and lagoon sludges. The goal was a commercially viable chemical process that could deal with these watery wastes and also process stored wastes (e.g. contaminated soils, solvents, oils, industrial wastes, pesticides and chemical warfare agents). Other companies and agencies at that time were focusing their efforts primarily on incineration and were investigating a variety of predestruction cleaning or dewatering processes to deal with the problem of aqueous wastes. The process described in this paper was developed with a view to avoiding the expense and technical drawbacks of incinerators, while still providing high destruction efficiencies and waste volume capabilities.

Following bench-scale testing supported by the National Research Council, a lab-scale process unit was constructed in 1988 and tested extensively. Based on the results of these tests, a mobile pilot-scale unit was constructed with funding support from the Canadian Department of National Defense. The pilot-scale plant was completed and commissioned in 1991. It was taken through a preliminary round of tests at Hamilton Harbor, Ontario, where the waste processed was coal-tar-contaminated harbor sediment. That demonstration received funding from both Environment Canada's Contaminated Sediment Treatment Technology Evaluation Program and the Ontario Ministry of Environment's Environmental Technologies Program. In 1992, the same unit was taken through a second round of tests as part of EPA's SITE program in Bay City, Michigan. This demonstration was partially funded by the Environment Canada Development and Demonstration of Site Remediation Technology Program, the Ontario Ministry of Energy and Environment Environmental Technologies Program and the Canadian Department of National Defense Industrial Research Program. In this test program, the pilot-scale unit processed PCBs in aqueous,

organic and soil matrices. This paper describes the process, the commercial-scale system under construction, and the results of demonstration testing in Canada and the United States.

Process Chemistry

The process involves the gas-phase reduction of organic compounds by hydrogen at temperatures of 850°C or higher. Chlorinated hydrocarbons, such as PCBs and polychlorinated dibenzo-p-dioxins (dioxins), are chemically reduced to methane and HCl, while nonchlorinated organic contaminants, such as PAHs, are reduced substantially to methane and minor amounts of other light hydrocarbons. The HCl produced can be recovered as acid or scrubbed out in a caustic scrubber downstream of the process reactor.

Figure B-1 shows some of the reduction reactions, including intermediate steps, for the destruction of a variety of contaminants using the ECO LOGIC Process. Unlike oxidation reactions, the efficiency of these reduction reactions is enhanced by the presence of water, which acts as a reducing agent and a source of hydrogen. The water shift reactions shown produce hydrogen, carbon monoxide, and carbon dioxide from methane and water. These reactions can be used at higher efficiencies by subjecting scrubbed methane-rich product gas to catalytic steam reforming, reducing the requirements for purchased hydrogen.

A benefit of using an actively reducing hydrogen atmosphere for the destruction of chlorinated organic compounds, such as PCBs, is that no formation of dioxins or furans occurs. Any dioxins or furans in the waste are also destroyed effectively. The reducing hydrogen atmosphere is maintained at more than 50% hydrogen (dry basis) to prevent formation of PAHs. This makes the scrubbed recirculation gas suitable for continuous monitoring using an on-line CIMS. By measuring the concentrations of intermediate reduction products, the CIMS produces a continuous indication of DE.

SE25 Commercial-Scale Process Unit

Figure B-2 is a schematic of the reactor where the destruction of the waste takes place. The various input streams are injected through several ports mounted tangentially near the top of the reactor. Special nozzles are used to atomize liquid wastes to accelerate liquid vaporization. The gas mixture

Table 14. Economic Analysis for the ECO LOGIC Reactor System

Activity	Utilization		
	60% (250 days)	70% (214 days)	80% (188 days)
Site preparation	\$127,400	\$127,400	\$127,400
Capital equipment	50,400	44,700	37,800
Start-up/mobilization	109,950	104,150	98,350
Labor	564,000	498,000	431,000
Supplies	110,000	106,000	103,000
Utilities	10,500	10,500	10,500
Residuals	2,500	2,500	2,500
Maintenance costs	4,000	3,500	3,000
Demobilization	20,000	20,000	20,000
Totals	\$998,750	\$916,750	\$833,550
Costs	\$2,000/ton	\$1,850/ton	\$1,670/ton

Table 15. Cost Extrapolations

	Cost, \$/ton	
	At actual throughput	At targeted throughput
60%	2,000	670
70%	1,850	620
80%	1,670	550

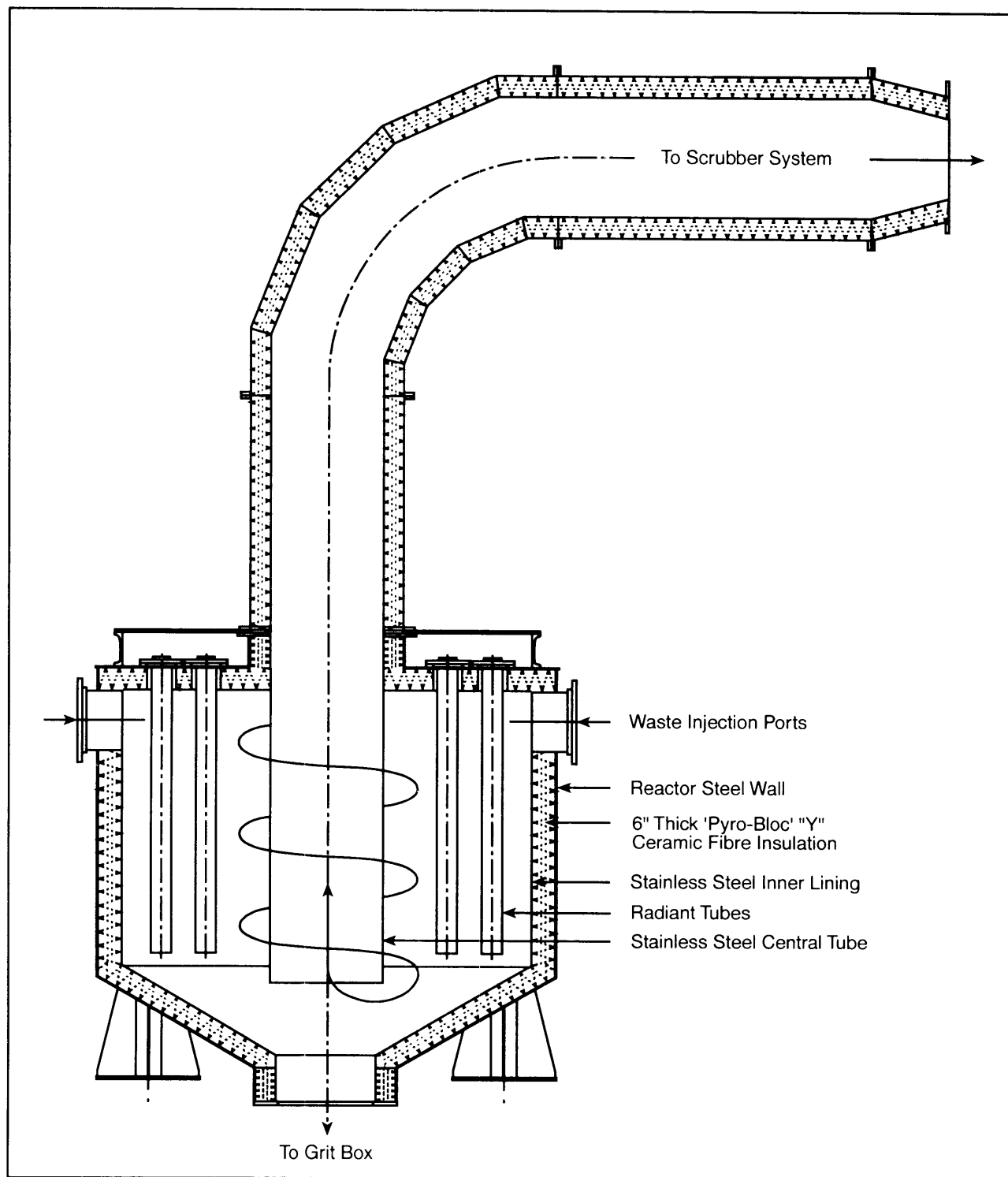


Figure B-2. Commercial-scale process reactor.

Table A-1. EPA Sample Locations

Stream	Description	Location
SS1	Wastewater	Feed line before pump
SS2	Waste oil	Oil drum
SS3	Contaminated soil	Feed drum
SS4	Caustic soda	Caustic soda reservoir tank
SS5	Scrubber make-up water	Feed line
SS6	Propane	Feed line
SS7	Hydrogen	Feed line
SS9	Combustion air	Boiler inlet
SS10	Treated soil	Treated soil collection drum
SS11	Reactor grit	Reactor grit catchpot
SS12	Scrubber sludge	Scrubber effluent tank
SS13	Scrubber decant	Scrubber effluent tank
SS14	Reformed gas	Duct after gas booster fan
SS15	Tank condensate	Bottom of condenser
SS16	Stack gas	Boiler stack
SS18	Heat exchanger	Heat exchanger residue waste drum
SS19	TDU gas	TDU-to-reactor feed line
SS20	TDU molten bath	Bath vessel
SS22	Scrubber liquor	Scrubber tank
SS24	Quench water	Quench water tank

Table A-2. ECO LOGIC Process Control Monitoring Stations

Parameter	Stations	Frequency	Method
Temperature	2, 3, 4, 5, 6, 7, 9, 11, 12, 13, 15, 16, 17, 18	Continuous	Thermocouple
Pressure	12, 13, 16, 1, 4, 7 7, 10	Continuous Continuous 1/2 hour	Pressure transmitter Differential pressure transmitter Gauge
Flow rate	7, 10 13 8	Continuous Continuous Hourly	Differential pressure transmitter Vortex flow meter Orifice meter
Feed rate	13 14	Hourly 1/2 hour	Vortex flow meter Tracer injection
pH	5	Continuous	pH meter
Gas constituents	7	Continuous	O ₂ analyzer; CIMS

trace of organic contamination and is then stored for analysis prior to discharge. Carbon can be regenerated on-site in the SBV, and the minor amount of scrubber sludge produced can also be processed through the TDM or SBV.

The cooled and scrubbed product gas is a clean dry mixture of hydrogen, methane, carbon monoxide, and other light hydrocarbons. Some of the gas is reheated and recirculated back into the reactor to increase the methane concentration in the reactor when processing low-strength wastes. Recirculation gas is also directed to the TDM as sweep gas, to the SBV as sweep gas, to the catalytic steam reformer for hydrogen generation, or to the compressor for storage.

Throughout waste processing operations, the product gas is sampled for analysis by the CIMS and other gas analyzers. The CIMS is capable of accurately monitoring up to 10 organic compounds every few seconds at concentrations ranging from percent levels down to ppb levels. It is used as part of the ECO LOGIC Process to monitor the concentrations of certain compounds indicative of the process DE. The compounds selected for monitoring depend on the waste being processed. For example, during PCB processing, monochlorobenzene is typically monitored as an indicator of DE. Low levels of this volatile compound indicate that destruction of the PCBs is proceeding to completion. The CIMS readings are monitored by the process control system, and the exceedance of alarm limits sends a message to the operator (low-level alarm) or automatically curtails waste input (high-level alarm). The CIMS also provides a continuous record of the quality of the product gas being compressed and stored.

Storage of the product gas under pressure permits the analysis of large batches of gas prior to using it as fuel and allows the operation of the system in a "stackless" mode. Should the product gas not meet the quality criteria established, there will have been no emissions to the environment, and the gas can simply be reprocessed. Potential applications for the stored product gas include heating the TDM, the catalytic steam reformer, and the steam boiler. If more gas is generated than can be used for fuel, an auxiliary burner located at the bottom of the common boiler/steam reformer stack is used.

Demonstration Testing

The pilot-scale process plant was tested for the first time at Hamilton Harbor, Ontario, in 1991. The waste processed during those tests was harbor sediment contaminated with

coal-tar at concentrations of up to 300 g/kg (dry weight basis). The harbor sediment was injected directly into the reactor as a 5-10% solids slurry, since at that time, the TDM had not been developed. The system had no catalytic steam reforming or gas compression and storage capabilities, and the product gas was sent directly to the dual-fuel boiler burner. DREs of 99.9999% were calculated (see Table B-1), based on the total organic input and the PAHs analysed in the boiler stack emissions.¹ During one test, the liquid waste input was spiked with PCBs to create a waste with a PCB concentration of 500 mg/kg. The concentration of PCBs in the air emissions, liquid effluent, and processed solids were below the detection limits for each, respectively. Based on the detection limits for the stack sampling trains, a PCB DRE of at least 99.9999% was achieved.

A second round of tests of the pilot-scale unit was conducted in 1992 in Bay City, Michigan, as part of the EPA SITE program. The wastes processed included oily PCB-contaminated water, high-strength PCB oil, and PCB-contaminated soil. As part of the demonstration, ECO LOGIC constructed and commissioned a prototype TDU, which was the forerunner of the current TDM, and demonstrated the capability to compress and store the product gas generated. The results for the test program, confirmed by EPA,² are shown in Table B-2. The SITE Program Project Bulletins and TER have been published and will be followed by the AAR.

The waste oil was obtained from beneath the Bay City landfill and was analyzed by EPA to contain 25% PCBs and percent levels of other chlorinated solvents. The contaminated soil was obtained from installation of the sump wells used to collect the oil, and the contaminated water was groundwater from the landfill. The test matrix called for three water/oil tests, three oil tests, and three soil tests.

The water/oil tests were to be nominally 4000 mg/kg PCBs, based on injecting the water and oil in a 100:1 ratio through the atomizing nozzle. Perchloroethene was added as a tracer compound. The oil tests were designed to process the high-strength oil at higher throughputs while demonstrating the ability to compress and store the product gas generated. Steam was added through a separate port, but liquid water was not co-injected with the PCB oil. Again, perchloroethene was added as a tracer compound. After oil waste processing, the stored gas was directed to the boiler for about 24 hours, and stack testing by the EPA subcontractor was conducted. The target DRE for the PCBs was 99.9999%, and this was achieved

Table B-1. Hamilton Harbor Performance Test Results

Run	Target Analytes	Conc. in Waste (mg/kg)	Decant Water Conc. (µg/kg)	Grit Conc. (mg/kg)	Sludge Conc. (mg/kg)	Stack Gas Conc. (µg/m ³)	DRE (%)
P1	PAHs	21,000	483	1.67	32.8	0.27	99.9999
P2	PAHs	30,000	680	7.76	56.1	0.23	99.9999
P3	PAHs	30,000	423	0.37	4.3	0.14	99.9999
P3	PCBs	500	ND	ND	ND	ND	99.9999

DRE = (Total Input - Stack Emissions) / (Total Input)

ND = Non-Detect

Table A-5. Liquids Sampling and Analytical Methods

Analyte	Analytical Principle	Reference
PCBs	GC/MS	EPA 680*
Dioxins/furans	HR GC/HR MS	EPA 8290*
CB/CP	GC/MS	EPA 8270*
PAHs	GC/MS	EPA 8270*
Volatile organics	GC/MS	EPA 8260*
Metals	CVAAS, ICAP	EPA 6010, 7470*
Organic halogens	IC	EPA 9020*
Inorganic halogens	IC	EPA 325.2
Hexavalent chromium	Colorimetric	EPA 7196*
Total sulfur	ICAP	EPA 6010*
TCLP volatiles	GC/MS	EPA 8240*
TCLP metals	CVAAS, ICAP	EPA 6010, 7470*
Ash	Combustion/gravimetric	EPA 160.4
Heating value	Bomb calorimeter	ASTM D240
Ultimate analysis	Combustion	ASTM D3176
Total organic carbon	GC	EPA 9060*
Density	Hydrometer	ASTM D1298
pH	pH meter	EP A9040*

* Using grab samples, performed in accordance with U.S. EPA Office of Solid Waste document *Test Methods for Evaluating Solid Wastes*, SW-846, 3rd Edition, Volume II Chapter 9, November 1986.

rently under construction has now achieved excellent results in lab-scale research and development supported by the National Research Council Industrial Research Assistance Program. Soils and sediments have been desorbed from ppm and percent levels down to low ppb levels, which are orders of magnitude below disposal criteria. Table B-3 shows the results of a number of lab-scale TDM runs processing a variety of waste types. The SE25 commercial-scale system now under construction has a design capacity of 100-300 tonnes/day of contaminated soil or sediment and 20 tonnes/day of PCB askarel fluid. The cost of processing these waste streams is estimated at \$400 and \$2,000 per tonne, respectively. The first SE25 system is being exported to Australia and will begin operations with a contract from Australian government agencies for 200 tonnes of obsolete pesticide destruction. Construction of a second SE25 system is also commencing to serve the North American market, and this unit should be commissioned for commercial use by the end of 1994. ECO LOGIC has made proposals to several major North American corporations and a number of government agencies for the cleanup of contaminated sites.

Treatability studies using ECO LOGIC's lab-scale destruction system are continuing. The lab-scale equipment includes a TDM for processing soil or sediment, and an SBV suitable for processing samples of chemical wastes or contaminated electrical equipment. Clients find that treatability studies are a cost-effective method for determining the applicability and effectiveness of the ECO LOGIC Process to their waste problems.

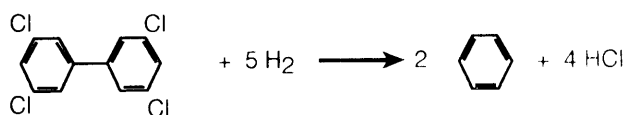
The ECO LOGIC Process is a proven technology for the destruction of high-strength PCB oil wastes and is suitable for the destruction of askarel fluids used in electrical equipment and PCBs and other organic contaminants in soils and sediments. ECO LOGIC offers a cost-effective alternative to incineration and can provide a complete on-site destruction service for the owners of hazardous organic wastes.

Table B-3. Summary of Test Results from the Lab-Scale Thermal Desorption Mill

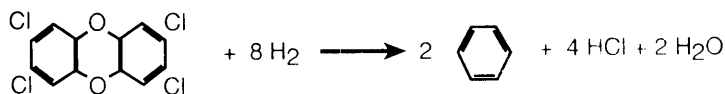
Waste Type	Waste PCB Concentration (ppm)	Grit PCB Concentration (ppm)
Soil (tarry, oily)	39	0.011
Soil (dry, sandy, PCB-spiked)	440	0.0039
Soil (dry, sandy, PCB-spiked)	520	0.0016
Sediment (muddy, fine, PCB-spiked)	710	0.028
Sediment (muddy, fine, PCB-spiked)	790	0.0097
Sediment (muddy, fine, PCB-spiked)	750	0.065
Sediment (muddy, fine)	7.3	0.0029
Sediment (muddy, fine)	8.3	0.0066
Sediment (muddy, fine)	8.3	0.0013
Sediment (muddy, fine)	420	0.0017
Sediment (muddy, fine)	420	0.012
Sediment (muddy, fine)	2000	0.044
Sediment (muddy, fine)	1200	ND (0.011)
Sediment (muddy, fine)	8.3	ND (0.005)

References

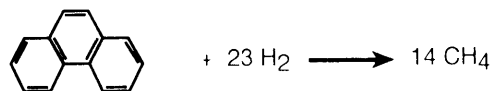
- 1 WTC Newsletter, published by the Wastewater Technology Centre, Environment Canada. No. 2, March 1992. Contact: Mr. Craig Wardlaw, Project Scientific Authority, 905-336-4691.
- 2 Technology Evaluation Report, SITE Program Demonstration, Risk Reduction Engineering Laboratory, U.S. EPA, Cincinnati, OH 45268, July 15, 1994. Contact: Mr. Gordon Evans, SITE Project Manager, 513-569-7684.



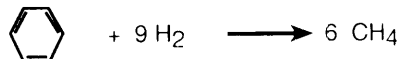
PCB molecule and hydrogen react to produce benzene and hydrogen chloride



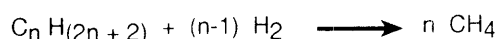
Dioxin molecule and hydrogen react to produce benzene, hydrogen chloride, and water



PAH molecule and hydrogen react to produce methane



Benzene and hydrogen react to produce methane



Hydrocarbons and hydrogen react to produce methane

Water Shift Reactions



Methane and water react to produce carbon monoxide and hydrogen



Carbon monoxide and water react to produce carbon dioxide and hydrogen

Figure B-1. ECO LOGIC process reactions.

swirls around a central stainless steel tube and is heated by 18 vertical radiant tube heaters with internal electric heating elements. By the time it reaches the bottom of the reactor, the gas mixture has reached a temperature of at least 850°C. The process reactions take place from the bottom of the central tube onward and take less than one second to complete.

Figure B-3 is a process schematic of the entire system, including the reactor. Most of the system components are mounted on highway trailers for ease of mobility. The reactor trailer houses the reactor, the electric heating control system, the scrubber system, the recirculation gas blower, the recirculation gas heater, and the watery waste preheater vessel. A second trailer contains the main power distribution room, the dual-fuel steam boiler, the catalytic steam reformer, and an auxiliary burner for excess product gas. Cooling water for the scrubbing system is generated by skid-mounted evaporative coolers, and scrubber stripping operations are carried out on a small skid situated near the boiler. The product gas compression and storage system is also skid-mounted to allow flexibility in site layout. For processing soils and other solids, the thermal desorption mill (TDM) is housed on a separate trailer, and the sequencing batch vaporizer (SBV) is a skid-mounted unit. The process control system, gas analyzer systems, and command center are housed in a standard office trailer. Several feed systems are available for various types of wastes, depending on whether watery waste, oil waste, or solid waste is being processed. Watery waste is preheated in a preheater vessel using steam from the boiler. The contaminated steam

from the preheater vessel is metered into the reactor at a rate determined by the process control system. Hot contaminated liquid exits the bottom of the preheater vessel at a controlled flow rate and enters the reactor through an atomizing nozzle. Oil waste can be metered directly from drums into atomizing nozzles using a diaphragm pump.

Solid wastes such as soil or decanted sediment are decontaminated in the TDM with the desorbed contaminants being sent to the reactor through a separate port. The internal workings of the TDM are designed to vaporize all water and organic contaminants in the waste soil/sediment while mechanically working the solids into a fine granular mixture for optimum desorption. The water vapor and organic contaminants are swept into the reactor by a sidestream of scrubbed recirculation gas.

Solids such as contaminated electrical equipment can be thoroughly desorbed using the SBVs. These chambers take advantage of the reheated recirculation gas stream to heat the equipment and carry contaminants into the reactor. The hydrogen atmosphere is nonreactive with most metals, and there are none of the problems with metal oxide formation associated with rotary kilns. The SBV can also be used for vaporization of drummed solid chemical wastes, such as hexachlorobenzene (HCB). Significant stockpiles of "hex wastes" exist and are still being generated as by-products of chlorinated solvent production. Advantages of vaporizing hex wastes directly from the drum include decreases in worker exposures

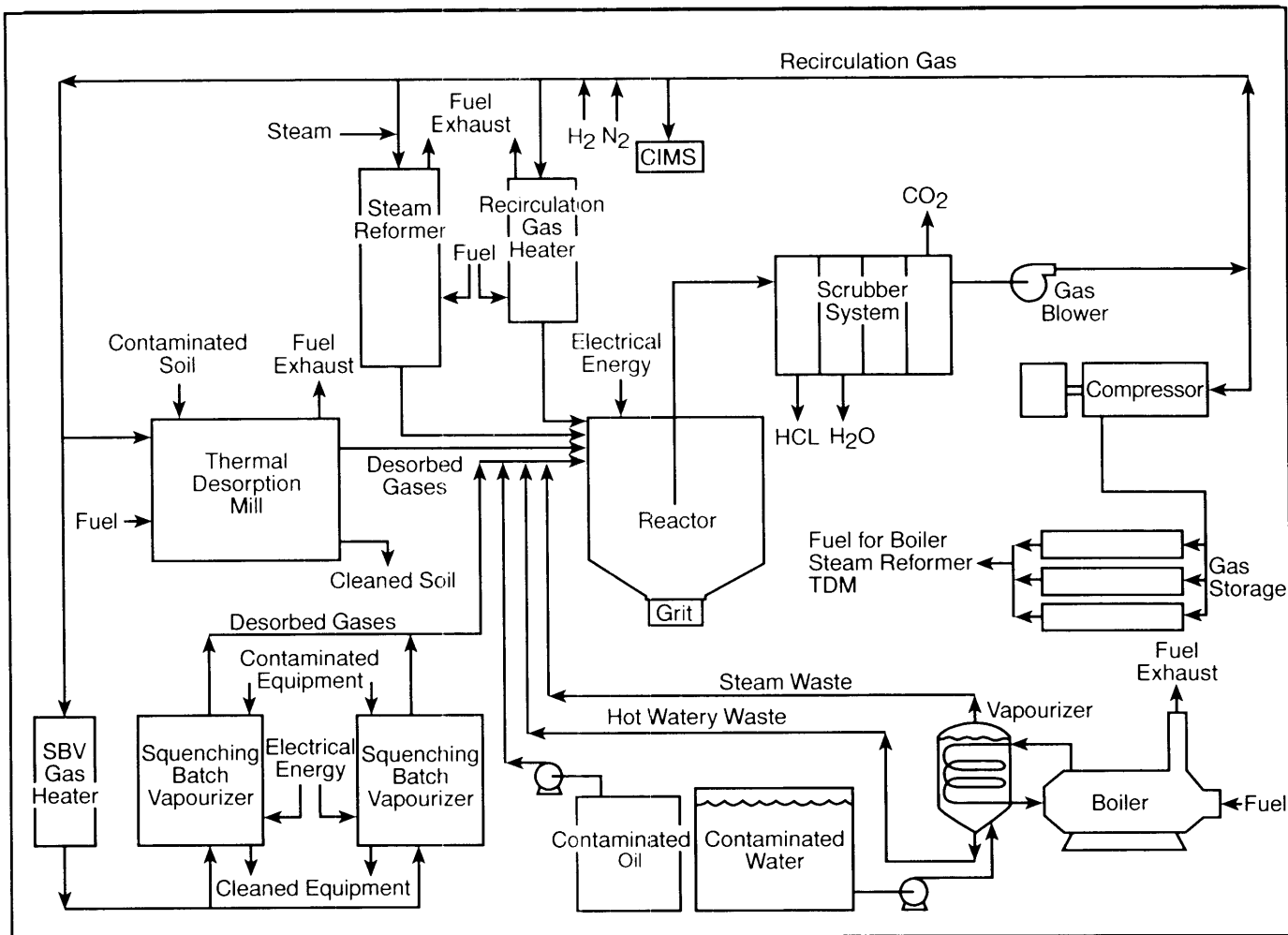


Figure B-3. Commercial-scale process unit schematic.

and fugitive emissions from drum transfer operations, cleaning of the drums in place, and segregation of inorganic contaminants into the existing drums. The SBV has been tested at lab-scale with hex waste samples and PCB-contaminated electrical equipment.

The product gas leaving the reactor is scrubbed to remove HCl, water, heat, fine particulates, aromatic compounds and carbon dioxide. The first stage of the scrubber can be operated to recover medium-strength HCl, which avoids the cost of neutralization with caustic. The cost saving can be considerable if the waste stream is heavily chlorinated, the acid can usually be recycled, and generation of large volumes of salty wastewater is avoided. The second stage of scrubbing drops the temperature of the gas to remove water and completes the removal of HCl by caustic packed tower scrubbing. Particulate matter, which may have entered the reactor as dissolved or suspended solids in the watery waste, is removed in both the first and second stages of the scrubber and is filtered out of the scrubber tanks continuously. Heat is removed using plate heat exchangers on the first two stages and cooling water from the evaporative cooling system.

The third stage of scrubbing removes low levels of benzene and naphthalene from the gas stream by neutral oil washing. The oil is stripped and regenerated with the benzene and naphthalene going to the inlet of the catalytic steam reformer. The fourth scrubbing stage is removal of carbon dioxide using monoethanolamine (MEA) absorption. The MEA is stripped and regenerated with the carbon dioxide going to the boiler stack.

The scrubber water from the stage-two scrubber leg returns to the covered section of the scrubber tank through a drop-tube that extends well below the water surface. This acts as a seal against air infiltration and as an emergency pressure relief mechanism. There will be no gas release if a short-term pressure surge forces gas out of the bottom of this tube since a check valve allows the gas to re-enter the system once the pressure returns to normal. The system normally operates within 10 in. water gauge (0.36 psi) of atmospheric pressure.

As waste is processed through the system, acid and water are produced as effluents. Filtered acid is pumped to a storage tank for further activated carbon treatment prior to recycling. Excess water is also filtered and carbon-treated to remove any

phosphorous, titanium, copper, and lead. ECO LOGIC suggested that some of the metals could be artifacts from the reactor's stainless steel inner liner because concentrations of manganese, titanium, copper, and lead in the waste were low. The primary metals in the waste included iron, calcium, sulfur, aluminum, magnesium, sodium, and phosphorous.

Runs 3 and 4 processed Hamilton Harbor sediment that was diluted to about 3% solids and spiked with approximately 1,000 ppm trichlorobenzene. These runs obtained a 99.99% DRE for the PAHs; for trichlorobenzene, 99.999% and 100.0000%, respectively. Solids reduction from destruction of organic materials averaged 60%.

Runs 6 and 9 processed Sheboygan Harbor sediment contaminated with PCBs. The waste was diluted to about 3% solids. The resultant PCB concentration in the feed ranged from 5 to 7 ppm. The runs achieved DREs of 99.999% and 99.99%; solids reduction averaged 15%.

Runs 7 and 10 processed Thunder Bay sediments contaminated with chlorophenols. ECO LOGIC reasoned that the sample matrix of the waste may have caused analytical procedure problems; the values obtained did not match ECO LOGIC's expectations. There were no problems in analyzing the other samples; ECO LOGIC reported DREs of 100.0000% [*sic*] and 99.999% for the two runs. Solids reduction was 40%.

Runs 5 and 8 processed Hamilton Harbor sediment diluted to about 3% solids. A large amount of naphthalene formed during these runs, resulting in net negative total DEs. However, naphthalene combustion in the quartz tube furnace was good. The DRE for Run 5 was 99.99%. Glassware breakage lost the Run 8 sample for the furnace XAD; the WTC lab audit analysis provided the DRE for Run 8.

A larger-scale test will likely provide better DREs because ECO LOGIC encountered a number of problems involving size restrictions. As these will be eliminated in pilot-scale tests, ECO LOGIC expects even better results than at bench scale.

Conclusions

The conclusions from this study were as follows:

- The bench-scale system demonstrated that the gas-phase chemical reduction reaction can decontaminate polluted harbor sediment.
- PAHs, especially large ones (coal), were more difficult to process than chlorinated wastes.
- Harbor sediments can contain amounts of organic material sufficient to show a substantial volume decrease after treatment. The treated solids were free of organic material.
- The test program demonstrated proof-of-concept on actual wastes.

Based on the interim results of the bench-scale test program, Environment Canada and Environment Ontario contracted ECO LOGIC to undertake a demonstration test program at Hamilton Harbor, funded by the Environment Canada Contaminated Sediments Treatment Program and the Ontario Environmental Technologies Program.

Case Study C-2: Pilot-Scale Demonstration of Contaminated Harbor Sediment

Introduction

ECO LOGIC's research and development on the treatment of harbor sediment began with laboratory testing of surrogate compounds, followed by the bench-scale tests described in Case Study C-1. The Canadian National Research Council Industrial Research Assistance Program, the Defense Industrial Research Program, the Environment Canada Contaminated Sediments Treatment Program, the Environment Ontario Environmental Technologies Program, and ECO LOGIC funded the work.

ECO LOGIC began construction of the mobile pilot-scale field unit during laboratory testing and undertook a demonstration program—the topic of this case study—at Hamilton Harbor, Ontario, Canada. ECO LOGIC installed its equipment on Hamilton Harbor Commission property, adjacent to a highly contaminated section of the harbor. The test ran from April to August, 1991.

Description

The pilot-scale research and development proceeded in four phases. First, laboratory testing proved the gas-phase chemical reduction reactions and established parameters for residence time, temperature, and ratios of hydrogen-to-waste. ECO LOGIC conducted these tests using laboratory glassware and a quartz tube furnace as a reactor. Next, a larger reactor (Case C-1) processed 5-10 liters of actual waste samples, primarily harbor and lagoon sediment. This established the capability of the process to treat actual wastes in complex matrices. During the third phase, ECO LOGIC developed a computer model to simulate operation of the reactor system. At the fourth phase, they built the pilot-scale reactor system and undertook proof-of-concept testing. This phase included materials, component, and system integrity tests to ensure leak-free system operation at the test temperatures, flow rates, and pressures.

ECO LOGIC designed the pilot-scale demonstration system to process contaminated harbor sediment. The system consisted of an electrically heated reactor that heated and mixed the watery sediment and hydrogen; a scrubber that removed particulates, heat, water, and hydrogen chloride from the gas product; a recirculation system that reheated most of the clean dry product gas for reinjection into the reactor; a boiler fueled by propane and the gas product; and a heat exchanger that steam-heated the watery sediment prior to injection into the reactor. Two standard drop-deck highway trailers held the entire system.

Table B-2. U.S. EPA SITE Program Results**Water/Oil and High-Strength Oil Tests**

Run	Waste Type	Contaminant	Concentration (mg/kg)	Target DRE/DE	Achieved
1	Water/Oil Tracer	PCBs	4,800	99.9999	Yes
		Perchloroethene	4,670	99.99	Yes
2	Water/Oil Tracer	PCBs	2,450	99.9999	Yes
		Perchloroethene	2,360	99.99	Yes
3	Water/Oil Tracer	PCBs	5,950	99.9999	Yes
		Perchloroethene	6,100	99.99	Yes
4	Oil Tracer	PCBs	254,000	99.9999	Yes
		Perchloroethene	33,000	99.99	Yes
5	Oil Tracer	PCBs	254,000	99.9999	Yes
		Perchloroethene	26,000	99.99	Yes
6	Oil Tracer	PCBs	254,000	99.9999	Yes
		Perchloroethene	34,000	99.99	Yes

Soil Tests

Run	Waste Type	Contaminant	Concentration (mg/kg)	Desorption Efficiency (%)
1	Soil Tracer	PCBs	538	94
		HCB	12,400	72
		OCDD	0.744	40
2	Soil Tracer	PCBs	718	99
		HCB	24,800	99.99
		OCDD	1.49	99.8

for all six tests. The target DE for the perchloroethene was 99.99% and this was also achieved for all six tests. The SITE program analytical results for the input concentrations of the water/oil mixture and the high-strength oil are shown in Table B-2.

Soils with various contamination levels were mixed to produce a relatively homogeneous quantity of soil with a nominal 1000 mg/kg PCB concentration. The soil test runs were conducted after construction and commissioning of the new TDU was completed. During the first TDU test, contaminated soil was processed with a desorption efficiency of 94%, resulting in a processed soil PCB concentration of 30 mg/kg. This result was encouraging for a first run, but the desorbed soil was still above the TSCA disposal criteria of 2 mg/kg. The waste soil residence time inside the TDU was increased for the second run, and a desorption removal efficiency of 99% was achieved according to SITE program results. The tracer compound used for the soil tests was HCB, which was spiked at significantly higher concentrations than the PCBs. The HCB was also contaminated with significant levels of octachlorodibenzo-p-dioxin (OCDD). The desorption efficiencies achieved for the HCB and OCDD for Test 2 were 99.99% and 99.8%, respectively. Due to TSCA permit restrictions, only two runs were performed for the third test condition. It should be noted that the performance of the TDU is independent of the destruction

process. The reactor destruction efficiencies for the desorbed contaminants were high for both TDU runs.

An additional component of the test program was a 72-hour endurance test aimed at demonstrating the continuous operation capabilities of the ECO LOGIC Process. The equipment operated perfectly and the 72-hour test was concluded successfully.

Current Status

The ECO LOGIC Process has been demonstrated to be a high-efficiency alternative to incineration for the destruction of PCB wastes. High water-content wastes and high-strength oils can both be processed with destruction removal efficiencies of at least 99.9999%. The ability to compress and store the product gases generated during processing means that no uncontrolled air emissions occur.

The existing pilot-scale unit is presently available for further research and development work including new applications such as mixed wastes (low-level radioactive PCBs), chemical warfare agents and explosives. Further research and development over the last 18 months has focused on optimizing the process for commercial operations, and improving the design of the soil/sediment processing unit. The TDM design cur-

Table C-5. Characterization Test Air Sampling Components

Polychlorinated aromatic compounds	Chlorobenzenes	Polychlorinated dibenzofurans	Polychlorinated dibenzo-p-dioxins
	Polychlorinated biphenyls	Chlorophenols	
Polyaromatic hydrocarbons	Naphthalene	Fluoranthene	Benzo(k)fluoranthene
	Acenaphthylene	Pyrene	Benzo(a)pyrene
	Acenaphthene	Benzo(a)anthracene	Ideno(1,2,3-cd)pyrene
	Fluorene	Chrysene	Dibenzo(a,h)anthracene
	Phenanthrene	Benzo(b)fluoranthene	Benzo(g,h,i)perylene
	Anthracene		
Combustion gases	Oxygen	Water vapor	Carbon dioxide

Characterization Tests—Table C-7 summarizes the results of the characterization tests. In all 12 tests, the PAH stack concentrations were low; they consisted primarily of naphthalene. Benzo-a-pyrene was not detected in any of the tests. The concentrations of total PAHs in the stack were below the Ontario Clean Air Program ambient air quality (AAQ) limits proposed for both naphthalene (30 µg/m³) and coal tar pitch volatiles (1 µg/m³). The chlorobenzene emission concentrations also were below the Clean Air Program AAQ guideline (35 µg/m³ for 1,2,4-trichlorobenzene). None of the sample trains contained chlorophenols, PCBs, or dioxins. Furans were detected during Characterization Test 5; ECO LOGIC attributes this to reactor pressure instability, resulting from a malfunctioning steam flow meter. The malfunction allowed the flow of waste steam to the reactor to increase substantially, causing the residence time, temperature, and DE to drop, producing furans from incomplete destruction of trichlorobenzene.

The residuals from the destruction process included grit from the bottom of the reactor, decant water from the scrubber, and scrubber sludge. The first six samples of grit contained mainly water, presented as water concentrations in units of µg/L (ppb). The next six tests were reported as dewatered concentrations of the solid material in units of ng/g (ppb). In general, the grit contained a total PAH concentration of several ppm. No PCBs appeared in the grit during any tests. The iron, zinc, and magnesium levels in the grit make it potentially recyclable as an ore for the steel industry. WTC collected the grit to test for various disposal or recycling options.

The laboratory analyzed the decant water for PAHs, PCBs, and metals. It did not contain detectable levels of PCBs for any of the tests. The levels of PAHs and metals in the decant water met the standards for sewer disposal.

Scrubber sludge consisted mainly of lime, carbon, fine particulates, and water; the sludge water characteristics were similar to those of the decant water. The sludge was contaminated with PAHs to some extent. Sludge metal content was low but increased as the sludge concentrated. Although the sludge was suitable for landfilling, it was more economical to recycle it into the water input stream.

Performance Tests—Table C-8 summarizes the results of the performance tests. During these tests, the system operated 24 hr/day, with periodic stoppages for maintenance.

Performance test stack emission sampling was more extensive than sampling for characterization tests. ECO LOGIC used three stack sampling trains per test to measure semivolatile trace organic compounds, VOCs, and metals. The semivolatile (MM5) train sampled the stack gas for PAHs, PCBs, chlorobenzenes, chlorophenols, dioxins, and furans; the volatile train (VOST) and metals train, for the compounds and metals shown in Table C-6. Continuous analyzers sampled the stack gas for oxygen, carbon dioxide, carbon monoxide, total hydrocarbons, water vapor, sulfur dioxide, and nitrogen oxides. The gaseous emissions were all within AAQ guidelines. The PAH and chlorobenzene concentrations in the boiler stack were below the Clean Air Program AAQ limits. There were no detectable emissions of chlorophenols, PCBs, dioxins, or furans. The results of the VOST testing indicated that all of the levels were lower than AAQ guidelines. The metals/particulate train measured metals and particulate emissions, which also met AAQ guidelines.

The feedstock grit, decant water, and scrubber sludge were analyzed for PAHs, PCBs, and metals; the feedstock analysis also included solids content and total organic content. The effluents from the performance tests were similar to the characterization tests. The grit was almost free of PAHs and contained no detectable PCBs. It had a total PAH concentration ranging from less than 1 ppm for Test 3 to 8 ppm for Test 2. Most of the contamination consisted of naphthalene. PCBs were not detected in the grit from any tests. The grit contained iron, calcium, magnesium, aluminum, potassium, and zinc.

Analyses of the decant water for PAHs, PCBs, and metals indicated no detectable levels of PCBs for any tests. PAHs and metals in the decant water were well below acceptable limits for sewer disposal.

PAHs contaminated the scrubber sludge. This sludge, when combined with the sludge produced during the characterization tests, was suitable for landfill disposal but could also have been reprocessed. The volume of sludge produced during the

Appendix C

Case Studies

Introduction

Two case studies illustrate the use and performance of the ECO LOGIC Gas-Phase Chemical Reduction Process.

Case Study C-1: Bench-Scale Demonstration on Contaminated Harbor Sediment

Introduction

Environment Canada asked for a series of laboratory tests on harbor sediment wastes prior to funding a pilot-scale unit. The Canadian Contaminated Sediment Treatment Technology Program provided funding for the tests.

Description

ECO LOGIC designed the 3 kg/hr reactor system to mimic the operation of the pilot-scale field demonstration unit, to provide DE data, and to develop the process control and continuous monitoring systems for the pilot-scale work.

As shown in Figure C-1, the reactor (LS) was a single cylindrical chamber with a 12-in. diameter and 72-in. length electrically heated by glo-bars passing through the central axis. The insulated reactor contained a relatively cool area (G) where solids collected after passing through the reaction zone. Thermocouples—at three locations inside and outside the inner stainless steel liner (T1-T6)—measured temperatures. Liquid waste (L) and hydrogen (H₂) flowed into the reactor at known, metered rates.

As the gases and fine particulates left the reactor, the CIMS drew a small sidestream; the remainder of the gas flowed to the first condensation flask. This flask (S) simulated the scrubber in the pilot system. After the first knockout flask, most of the gas flow passed through a heat exchanger tube (HX), condensing the rest of the water in the second knockout flask (KO). A valved pump (P) and rotameter (R) drew some of the gas through an XAD2 resin trap cartridge (X). The remaining gas was vented (V). Analyses of the scrubber flask water, the knockout flask water, and the XAD2 resin determined the reactor's DE.

A second sidestream, drawn from the main stream immediately after the scrubber flask (S) passed through a quartz tube

furnace (Q), along with air for combustion. This stream simulated the DE obtained by using the boiler and reactor combination. After drying in a water knockout flask, the gas stream passed through an XAD2 resin tube to a valved pump and rotameter.

Monitored process parameters included the hydrogen flow rate, reactor pressure, reactor temperatures, boiler temperature, scrubber flask temperature, knockout flask temperature, and quartz oven temperature. The CIMS also monitored and recorded concentrations of 10 organic compounds.

Testing Protocol

Each run processed about 5 liters of sediment over a period of several hours. Environment Canada provided eight sediment samples: four from Hamilton Harbor, two from Sheboygan Harbor, two from Thunder Bay Harbor, and two from Hamilton Harbor that were subsequently spiked with trichlorobenzene (Table C-1). ECO LOGIC performed analysis on the samples, except for the metals analyses, which were done by XRAL Environmental.

Half of the samples were split for duplicate analysis by the Wastewater Technology Center Laboratory, whose personnel also observed most of the test runs. For two test runs, the laboratory analyzed samples for dioxins, furans, PCBs, PAHs, organo-chlorines, base neutrals, chlorobenzenes, chlorophenols, and metals; for the other runs, only target compounds.

To begin the test, the operator charged a measured amount of well mixed sediment to the waste flask (boiler). After the test, the operator emptied the flask and recirculation pump and then flushed them with a measured volume of water. The test operator combined some of the exit sample extracts prior to analysis. Table C-2 lists the final five output samples.

Data Summary

Table C-3 summarizes the results of the ten test runs requested by Environment Canada. Runs 1 and 2 processed Hamilton Harbor sediment diluted to about 4% solids. Both tests obtained a 99.99% DRE. Run 1 samples received full analysis; there were no dioxins or furans in any of the samples, including the waste. Runs 1 and 2 achieved a solids reduction of about 80%; the remaining grit contained no PAHs. A metals analysis of the grit from Run 1 revealed sodium, manganese,

Table C-7. Characterization Test Results

Test number	1	2	3	4	5	6
Waste input (kg)	200	250	350	400	250	350
% Solids	5	5	5	5	6	6
% Organics	30	30	30	28	32	32
Stack concentration (ng/DSCM)						
PAHs	1000	999	260	1000	140	460
Chlorobenzene	70	100	19	510	34000	27
Chlorophenol	0	0	0	0	0	0
Emission rates (ng/s)						
PAHs	66	96	19	82	8.9	33
Chlorobenzene	4.5	9.8	1.4	40	2100	1.9
Chlorophenol	0	0	0	0	0	0
Reactor grit						
PAHs (µg/L)*	2.3	3.6	2.2	43.5	4.1	10.2
PAHs (ng/g)*						
Metals (µg/ml)**	—	ND-0.26	ND-0.06	ND-8.52	ND-9.72	ND-6.04
Metals (µg/g)**						
Scrubber decant H ₂ O						
PAHs (µg/L)*	1.5	0.8	1.6	0.5	1.9	2.1
Metals (µg/ml)**	ND-0.05	ND	ND-0.06	ND-0.65	ND-0.12	ND-0.12
Scrubber sludge						
PAHs (µg/L)*	66.0	48.2	30.6	30.4	25.3	41.5
Metals (µg/ml)**	ND-0.39	ND-0.03	ND-0.02	ND-0.09	ND-0.44	ND-0.14
Waste input (kg)	240	240	240	240	240	122.5
% Solids	9	8	8	8	9	6
% Organics	28	28	28	28	29	32
Stack concentration (ng/DSCM)						
PAHs	190	620	160	250	280	370
Chlorobenzene	11	28	11	13	11	10
Chlorophenol	0	0	0	0	0	0
Emission rates (ng/s)						
PAH	17	37	11	18	20	20
Chlorobenzene	0.98	1.6	0.77	0.92	0.84	0.72
Chlorophenol	0	0	0	0	0	0
Reactor grit						
PAHs (µg/L)*						
PAHs (ng/g)*	252.1	617.1	192.4	61.5	423.0	292.4
Metals (µg/ml)**						
Metals (µg/g)**	ND-3.61	ND-550	ND-220	ND-260	ND-250	ND-240
Scrubber decant H ₂ O						
PAHs (µg/L)*	1.1	1.1	2.4	2.5	5.4	7.8
Metals (µg/ml)**	ND-0.17	ND-0.07	ND-0.2	ND-0.07	ND-0.05	ND
Scrubber sludge						
PAHs (µg/L)*	4.5	34.0	89.3	42.2	78.3	1124.2
Metals (µg/ml)**	ND-0.84	ND-1.64	ND-0.66	ND-0.85	ND-5.18	ND-40.7

* Average of 16 PAH compounds.

** Reporting only 40 CFR 261 Appendix VIII metals

ND Not detected.

Table C-1. Sediment Samples

Run	Source	Input Analysis	Output Analysis	Target Compound	WTC Lab Duplic.	Mass Balance
1	Hamilton	Full	Full	N/A	No	Yes
2	Hamilton	Target	Target	PAHs	Yes	Yes
3	Ham/TCB	Target	Target	PAHs/CBs	Yes	Yes
4	Ham/TCB	Target	Target	PAHs/CBs	No	Yes
5	Hamilton	Target	Target	PAHs	No	Yes
6	Sheboygan	Target	Target	PCBs	No	Yes
7	Thunder Bay	Target	Target	CPs	Yes	Yes
8	Hamilton	Full	Full	N/A	Yes	Yes
9	Sheboygan	Target	Target	PCBs	Yes	Yes
10	Thunder Bay	Target	Target	CPs	No	Yes

Table C-2. Residue Streams

Sample	Type	Component Source
Reactor grit	Solids	Reactor
Scrubber catch	Solids Liquid	Scrubber flask, lines Scrubber flask
Scrubber exit	Solids Liquid	Heat exchanger, KO flask, lines Heat exchanger, KO flask, lines
Scrubber exit	Gas	XAD2 resin
Incinerator exit	Liquid Gas	Knockout flask XAD2 resin

Table C-3. Performance Results

Run	DRE*	DE	Recirc. Rate	Solid Content	Solids Reduction
1	99.9939	67.9	98.4	4.2	87.4
2	99.9960	85.2	98.4	3.6	76.7
3 PAHs	99.9980	61.3	98.4	3.1	49.3
CB	99.9990	99.9954			
4 PAHs	99.9944	81.6	98.4	3.2	70.9
CB	100.0000	99.9999			
5	99.9911	-150.2	98.4	3.0	9.7
6	99.9990	99.4	98.4	3.0	2.7
7	100.0000	100.0	98.4	17.6	32.6
8	99.9836	-1.1	98.4	3.0	7.0
9	99.9941	99.8	98.4	3.5	25.8
10	99.9960	96.8	98.4	8.0	43.4

* DREs based on total organics fed and PAHs analyzed in the stack.

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